2852

H M Lancaster

B
~~Tech~~
~~A~~

AMERICAN SOCIETY

m

FOR

TESTING MATERIALS

AFFILIATED WITH THE
INTERNATIONAL ASSOCIATION FOR TESTING MATERIALS

PROCEEDINGS

OF THE

TWENTY-FIRST ANNUAL MEETING

Held at Atlantic City, New Jersey
June 25-28, 1918

555336
16.12.52

VOLUME XVIII
PART II. TECHNICAL PAPERS

EDITED UNDER THE REGULATIONS GOVERNING PUBLICATIONS
Office of the Society, University of Pennsylvania, Philadelphia, Pa.

PUBLISHED BY THE SOCIETY

1918

TA
401
A5
v.18
pt.2
cop.2

Entered according to Act of Congress by the
AMERICAN SOCIETY FOR TESTING MATERIALS,
in the office of the Librarian of Congress, at Washington.

The Society is not responsible, as a body, for the statements and opinions advanced in this publication.

CONTENTS.

TECHNICAL PAPERS.

PAGE

Topical Discussion on Cooperation in Industrial Research.

Opening Announcement—Edgar Marburg........................ 5
General Introduction—Henry M. Howe........................ 8
Recent Developments in Great Britain—John Johnston............ 12
Organization of Industrial Research—Arthur D. Little............ 22
Developments in Industrial Research—Charles L. Reese............ 32
Cooperative Research in the American Canning Industry—Frank E. Gorrell........................ 40
Development of Existing Agencies—Alfred D. Flinn............ 43
Cooperation of the Portland Cement Association and Lewis Institute in Experimental Studies of Concrete—Duff A. Abrams............ 56
Some Practical Views of Research—J. S. Unger............ 62
Cooperation between Governmental Bureaus and the Industries in Research on War Problems—S. R. Church............ 66

Ferrous Metals.

Grain Size of Iron as Affected by Temperature—D. J. McAdam, Jr..... 68
Discussion........................ 82
Changes Within the Critical Range of a Given Steel: From Ac_1 to Ac_{3-2}—J. G. Ayres, Jr........................ 87
Cast Steel Anchor Chain—H. Jasper Cox........................ 98
Discussion........................ 114

Non-Ferrous Metals.

Topical Discussion on Season and Corrosion Cracking of Brass.

Season Cracking and Splitting of Condenser Tubes and Pipes—William Campbell........................ 147
The Causes and Prevention of Corrosion Cracking—H. W. Bassett.. 153
Season Cracking—W. Reuben Webster........................ 163
Initial Stress and Corrosion Cracking—P. D. Merica and R. W. Woodward........................ 165
The Prevention of Season and Corrosion Cracking of Brass Artillery Cases by Special Heat Treatment—W. B. Price............ 179
The Use of Mercury Solutions for Predicting Season Cracking in Brass—Henry S. Rawdon........................ 189
General Discussion........................ 201
The Evaluation of Zinc Dust: A Proposed Method of Analysis—L. A. Wilson........................ 220

Cement, Concrete and Ceramics.

PAGE
Proportioning the Materials of Mortars and Concretes by Surface Areas of Aggregates—L. N. Edwards........ 235
Discussion........ 284
Effects of Grading of Sands and Consistency of Mix Upon the Strength of Plain and Reinforced Concrete—L. N. Edwards........ 303
Effect of Age on the Strength of Concrete—Duff A. Abrams........ 317
The Necessity for Inspection and Testing of Refractory Brick—C. E. Nesbitt and M. L. Bell........ 336
Discussion........ 346
Silica Cement—R. J. Montgomery........ 350

Miscellaneous Materials: Preservatives, Coatings, etc.

The Standard Saybolt Universal Viscosimeter—Winslow H. Herschel........ 363
The Variable-Pressure Method for the Measurement of Viscosity—E. C. Bingham........ 373
Discussion........ 384
Internal-Combustion Engine: Lubrication and Lubricants—P. H. Conradson........ 387
The Sampling of Deposits of Road Stone and Gravel in the Field—L. Reinecke and K. A. Clark........ 393
Discussion........ 414
An Abrasion Test for Stone, Gravel and Similar Aggregates—H. H. Scofield........ 416
Discussion........ 426

Testing Apparatus and Methods of Testing.

Transverse Testing under Non-Uniformly Distributed Load with Special Application to Airplane Wing Ribs—Irving H. Cowdrey........ 429
A Simple Type of Brinell Testing Machine for 500 kg. Load—A. V. de Forest........ 449
A New Method of Obtaining Brinell Hardness—J. G. Ayers, Jr........ 460
Discussion........ 466
Sumner Elastic-Limit Recorder—J. L. Jones and C. H. Marshall........ 478

Subject Index........ 484
Author Index........ 491

TOPICAL DISCUSSION ON COOPERATION IN INDUSTRIAL RESEARCH.

OPENING ANNOUNCEMENT.

By Edgar Marburg.[1]

This discussion on "Cooperation in Industrial Research" had its origin in a suggestion from Dr. John Johnston, Secretary of the National Research Council, and a member of this Society. In support of this suggestion Dr. Johnston submitted a written statement which impressed the writer so forcibly that he should like to quote from it as follows:

> "One of the most striking consequences of the war is the increasing general realization of the primary importance of scientific research to the whole question of national defense, as well as to the successful prosecution of industry and the greatest measure of economy of resources after the war. . . . Impressed by the paramount importance of promoting the application of science to industry in this country, the National Research Council has taken up the question of the organization of industrial research; it believes that this matter should be furthered in every way possible and as rapidly as may be for the following reasons: In the first place, because of the necessity of rapid technical advance in many industries if we are to compete successfully with other nations both now and after the war; secondly, because any steps taken in this direction will react immediately to further the general appreciation of science and of its usefulness when applied; thirdly, because the present time is conducive to the growth of new ideas—indeed such a favorable opportunity may not recur.
>
> "Accordingly the National Research Council has inaugurated an Industrial Research Section, which shall consider the best methods of achieving such organization or research within an industry, or group of related indus-

---

[1] Secretary-Treasurer, American Society for Testing Materials.

> tries (for example, industries using the same raw materials, or with similar waste products). It considers that cooperation between capital, labor, science and management constitutes the best general means of financing and directing the extended laboratory investigations and the large-scale experimental and developmental work required for adequate industrial research. In pursuance of this general plan, it proposes to establish an Advisory Committee, composed of strong men with the imagination to foresee the general benefits which would certainly follow from the further progress of science and from a more general and more thorough application of science to industry."

It was realized at once that the institution of a carefully planned topical discussion on this general subject might be expected to afford the Society an unusual opportunity to render a worthy national service in the field with which it has long been prominently identified. It was accordingly decided to make it one of the leading features of this, the Twenty-first Annual Meeting of the Society: first, by devoting an entire evening to it; and second, by having it somewhat formally introduced with the recital, in so far as possible, of successful experiences in the practical application of industrial research, which might be expected to lead to helpfully suggestive queries and answers stimulating to others who may have hitherto failed to discern that equally promising or better opportunities have lain latent at their own doors, and who would welcome an awakening that might result in making such resources available to the nation, not only in this hour of innumerable needs, but also in relation to plans for the post-bellum period when the economic future of every nation will be so largely determined by the position to which it may have previously attained in problems of industrial research.

Indeed, if the war has proved one thing, it is that not only the safety of a nation in war but even its protection against the menace of war, depends largely on the degree to which she has attained *complete independence* from other nations in the matter of resources essential to the prolonged conduct of war. By "resources" is meant not merely physical things, such as raw materials, needed in the greatest variety and abundance, and adequate means of transportation, but the sum total of scientific knowledge and technical skill at the command of the nation. It is to the importance of this last that this topical discussion is especially designed to direct attention.

In order that the fruits of the discussion may be garnered to the full, every member of the Society is urged to endeavor to add his mite by drawing on his own experiences and observations, and making his contribution as promptly as possible in carefully considered written form. The intention is to give precedence on the floor to written rather than verbal discussions, and to have the former available in so far as practicable in printed form on the evening of Wednesday, June 26, for which this discussion has been scheduled.

Upon the conclusion of the written discussions received in advance of this session, the subject will be thrown open to general informal, verbal discussion, in which it is hoped every member will find an opportunity of participating.

GENERAL INTRODUCTION.

BY HENRY M. HOWE.[1]

A very great advance towards cooperation in industrial research was made in 1868, when on the initiative of Sir Lowthian Bell, the Iron and Steel Institute came into being, and replaced the habitual secretiveness of the British iron master with discussion of the principles and practice of his art. Only three years later, in 1871, the American Institute of Mining Engineers was founded under the stimulating leadership of Holley, Drown, and Raymond for a like but even broader effort to replace secrecy with discussion.

Another great leader, Judge Gary, took an important step when he started his steel-makers' dinners, and brought those who had been intent chiefly on cutting each others throats into aiding each other.

And now we propose another step, that wherever feasible, the industries shall not only permit such disclosure and discussion of their discoveries as occur at the meetings of technical societies, but shall cooperate in making their discoveries. The advantages of this plan are naturally inversely as the size of the individual corporation. Cooperation in research between small companies lessens the disadvantage of their smallness. To corporations so large that they feel but lightly the cost of their researches, the advantages of cooperation will weigh correspondingly lightly against its apparent disadvantage of transferring capital in the form of knowledge to others who may not repay in full.

Small manufacturing companies so fortunate as to feel that they can trust each other may well look at cooperative research as simply one step in the inevitable enlightenment of human ways. Each step has seemed visionary and Quixotic to those who lack vision, but to the natural leaders it has seemed an obvious extension of the displacement of antagonism by cooperation. The setting up of specifications and standards of reasonableness by this society is one example. Another is the formation of conferences between the selling departments of the competitors in a given industry.

---

[1] Chairman, Engineering Division, National Research Council.

Though the immediate motive for founding an industry is to make money, yet in another sense each exists primarily to serve the public and incidentally to gain for its projectors and managers a just reward for their courage in supplying funds and for their skill and energy in using them, for their product can be sold only as the public profits by buying it. The pecuniary reward should be roughly proportional to the benefit given the public. Clearly John and James can jointly serve the public better, and hence can command greater pay from the public, that is greater profits, if each serves the public not with his own knowledge alone but with that of his competitor as well.

Every research consists of four tolerably distinct parts: selection, planning, execution, and interpretation.

First, out of the immeasurable area of our ignorance we select a certain limited field the exploration of which promises the greatest profit. The problem to be solved should be enunciated with perfect sharpness The selection of this field demands to-day first a knowledge of the problems which are pressing on our military and other departments, and second, very sound judgment. In other times the pressing needs of the industry dictate the selection. How much good energy has been wasted in the desultory exploration of some little plot which has happened to catch the young investigator's fancy?

Second, the research should be so planned that its results will have the greatest promise of yielding a clear and decisive solution of the problem, a sharp answer to a sharp question. This requires complete familiarity with the subject, and especially with existing knowledge and with the tests applicable. For instance, if we study the influence of a process on the mechanical properties of a metal or other product, we should either provide for tests which will measure directly the properties needed in the service in view, or if as usual we cannot reproduce in our tests the most trying conditions of service, then we should provide plural kinds of tests, increasing the number of kinds in proportion to the indirectness of their evidence as to fitness for service. Every kind of test which throws light on service fitness should be used. The consideration that new and unforeseen services are constantly developing argues for widening the range of tests for any given product.

Third, the process itself should be instituted and these several tests be made by those thoroughly familiar with them, each detail going to an expert.

Fourth, the results should be interpreted in a strictly philosophical spirit, without bias or reference to preconceived hypotheses. This work of interpretation should indeed be open to all connected with the research, yet because what is everyone's duty is no one's, certain men should be charged directly with this vital task, knowing well that their inferences are subject to review by all their colleagues and will be accepted only as they are just and reasonable.

Each of these four phases of research requires special qualifications in its executor: For selection, prophecy and breadth of view; for planning, imagination and administration; for execution, skill and trustworthiness; for interpretation, philosophy.

This mere recitation of the needs of research is a demonstration of the need of cooperation, for it is only a few of the laboratories of the very great industries that have either the various kinds of men with these various gifts, or the means to experiment on so wide a scale. Scattered through the many institutions of learning and the laboratories of the smaller industrial works there are innumerable investigators, each with certain intellectual gifts, each skilled in certain kinds of tests, but few with broad knowledge of the needs of the Government or of any given industry to guide them in their selection; relatively few with the breadth of view needed for wise planning; very few if indeed any with skill in all the different kinds of tests needed; and relatively few endowed with the philosophical spirit needed for interpretation. Yet these men collectively have enormous potencies for research, if their several gifts and skills can be brought into broad cooperation. How often do we see results reached with extraordinary patience and accuracy not utilized but prostituted to support a preconceived hypothesis which, rightly viewed, they discredit?

It is our defect as a race that this sort of team play comes less naturally to us than isolated individualistic research, in which each man obeys his own impulses, and is a law unto himself. But as with men so with nations, development implies first of all the cure of our inborn defects. That the unmitigatedness of our individualism is a defect we are reminded sharply by the present grave threat of our national enslavement by a people far less intelligent, energetic, and self-controlled than we, but as coherent as we are incoherent, as given to team play, as desirous of support, as we are self-reliant and detached. Distasteful as it is to us to act on our motto of "United we stand, divided we fall," if we are to survive our strong units must learn to cohere.

Experience with cooperative research has proved abundantly that, wisely directed, it may stimulate instead of lessen individual initiative, which is of the first importance.

One of the aims of the National Research Council is to induce the cooperative spirit wherever possible in industrial research, and research for the immediate benefit of the Government. The Engineering Division of the Council expects to devote part of its energies to this work, and here it counts confidently on the support of this society. It asks you as individuals and as a body to aid it by pointing out fields in which cooperative research is urgently needed, by advice in planning our researches, by the aid of your industrial and collegiate laboratories in executing the tests, and by your wisdom in discussing the results. It hopes that you will cooperate with it and it with you.

RECENT DEVELOPMENTS IN GREAT BRITAIN.

By John Johnston.[1]

The commanding position held for so long by a large number of British industries had created a deeply rooted feeling of security among a large body of manufacturers; this, coupled with a natural conservation and with the circumstance that the heads of many industries have not been educated in such a way as to enable them to appreciate scientific knowledge, was a hindrance to the adoption of proposals for research work in industry there. It had not been generally realized that industrial conditions were changing, and that many of the conditions which originally enabled British industries to assume a preeminent position had ceased to exist. The war, however, brought this fact home, and produced a change in attitude which otherwise would have required a very much longer period to achieve; directly, by the necessity of many lines of research work to the production of munitions and to the prosecution of the war in general; indirectly, by the fact that many firms were forced to adapt themselves to entirely different lines or methods of manufacture, many of which depended for their development upon research work. British scientific men had for years been pointing out the necessity for the greatly extended application of science to industry, but no definite action was ever taken until about a year after the beginning of the war when a White Paper,[2] signed by Arthur Henderson, at that time a member of the British Cabinet, appeared.

This document is entitled "Scheme for the Organization and Development of Scientific and Industrial Research;" its first paragraph is so pertinent that it is quoted here:

> "There is a strong consensus of opinion among persons engaged both in science and in industry that a special need exists at the present time for new machinery and for additional State assistance in order to promote and organize

---

[1] Secretary, National Research Council.

[2] Cd. 8005; July 23, 1915.

> scientific research with a view especially to its application to trade and industry. It is well known that many of our industries have since the outbreak of war suffered through our inability to produce at home certain articles and materials required in trade processes, the manufacture of which has become localized abroad, and particularly in Germany, because science has there been more thoroughly and effectively applied to the solution of scientific problems bearing on trade and industry and to the elaboration of economical and improved processes of manufacture. It is impossible to contemplate without considerable apprehension the situation which will arise at the end of the war unless our scientific resources have previously been enlarged and organized to meet it. It appears incontrovertible that if we are to advance or even maintain our industrial position we must as a nation aim at such a development of scientific and industrial research as will place us in a position to expand and strengthen our industries and to compete successfully with the most highly organized of our rivals. The difficulties of advancing on these lines during the war are obvious and are not underestimated, but we cannot hope to improvise an effective system at the moment when hostilities cease, and unless during the present period we are able to make a substantial advance we shall certainly be unable to do what is necessary in the equally difficult period of reconstruction which will follow the war."

By this document the State had "recognized the necessity for organizing the national brain power in the interests of the nation at peace. The necessity for the central control of our machinery for war had been obvious for centuries, but the essential unity of the knowledge which supports both the military and industrial efforts of the country was not generally understood until the present war revealed it in so many directions as to bring it home to all. War has remained as much an art as ever, but its instruments, originally the work of the craftsman and the artist, are now not only forged by the man of science; they need a scientific training for their effective use. This is equally true of the weapons of industry. The brains, even the very processes, that to-day are necessary to the output of munitions were yesterday needed, and will be needed again to-morrow, for the arts of peace. This is the central fact which justifies the establishment of the new machinery in the midst of a struggle that is absorbing the whole energies of the nation in a way no previous war has done."[1]

The scheme thus promulgated is designed to establish a permanent organization for the promotion of scientific and industrial research; it provides for a small advisory council, "composed mainly of eminent scientific men and men actually engaged in industries dependent upon scientific research," whose primary functions are to advise on proposals

"(1) for instituting specific researches;

(2) for establishing or developing special institutions or departments of existing institutions for the scientific study of problems affecting particular industries and trades;

(3) for the establishment and award of Research Studentships and Fellowships."

It is unnecessary to give further details here, except to state that the Council was directed to frame a program for their own guidance in recommending proposals for research, which "will naturally be designed to operate over some years in advance, and in framing it the Council must necessarily have due regard to the relative urgency of the problems requiring solution, the supply of trained researchers available for particular pieces of research, and the material facilities in the form of laboratories and equipment which are available or can be provided for specific researches."

In accordance with these instructions, the Council made a survey of the whole field, and as a preliminary measure gave aid and encouragement to a number of researches which were being carried on by various technical societies, institutions or committees. This list of researches, with which the members of the Society may not be familiar, is of interest:

Laboratory glass; optical glass; glass technology.
Hard porcelain; refractory materials.
Setting and disintegration of salts and crystallin substances.

---

[1] Report of the Committee of the Privy Council for Scientific and Industrial Research for the year 1915-16 (Cd. 8336), page 9. Much of what follows is taken from this report and from that for the year 1916-17 (Cd. 8718), both of which should be consulted.

Tin and tungsten.
Corrosion of non-ferrous metals.
Properties and composition of alloys.
Tool steel experiments.
Statistical work in preparation of field for research in iron and steel.
Methods of notched bar impact testing; hardness test for journals and pins.
Flow of steam through nozzles.
Rate of heat transmission from hot surfaces to fluids over them.
Deterioration of structures of timber, metal, and concrete in sea water.
De-gumming of silk.
Heating of buried cables.
Properties of insulating oils.

The main work of the Advisory Council, however, was concerned with the organization of industrial research; firstly because they felt "the paramount importance of arousing and securing the interest of manufacturers in the application of science to industry, and secondly because the influence of the war has created in industry an atmosphere conducive to the growth of new ideas, whereas it has unfortunately made the prosecution of work in pure science and in its organization a matter of extreme difficulty." As its work along these lines developed, it became clear that a separate organization having its own estimates in charge of a minister responsible to Parliament was a necessity. Accordingly in December, 1916, there was established a separate Department of State entrusted with the organization of scientific and industrial research; and under this Department an Imperial Trust was created to hold, on behalf of the Department, the sum of one million sterling which Parliament had placed at its disposal to be spent over a period of five years or so.[1] It was agreed that the money thus made available should be spent in the form of grants in aid of research undertaken by firms in any industry which may combine to conduct it on a cooperative basis; and that the best means to this end is the establishment of Trade Research Associations.

---

[1] In addition to this sum there is an annual appropriation to cover (*a*) the cost of those researches which will not be undertaken by the Research Associations; (*b*) the grants to individual workers, both students and others; (*c*) the cost of administration. The Department now is in charge of the National Physical Laboratory, which heretofore was supported largely by the Royal Society; and has established a Fuel Research Board to deal effectively and systematically with the urgent problem of fuel economy.

A leaflet[1] has been published explaining the manner in which such associations are expected to work, from which we take the following excerpt:

> "The independence and initiative of the British manufacturer have contributed largely in the past to his success. After the war he will need all possible assistance in undertaking and developing research work as a means of enlarging his output and improving its quality. But if the help is to be effective, it must increase his independence and initiative. It must avoid chaining him to the routine of Government administration however efficient. It must be so given as to enlist his active support. To the initiative of the manufacturer, the improvement of old and the discovery of new industrial processes in this and other countries have largely been due. It has been the cooperation of progressive industry with science which has led to the practical application of the results obtained in the laboratories of scientific men. The Advisory Council for Scientific and Industrial Research have, therefore, recommended after consultation with manufacturers and others that the new fund should be expended on a cooperative basis in the form of liberal contributions by the Department towards the income raised by voluntary associations of manufacturers established for the purpose of research. By this method the systematic development of research and the cooperation of science with industry will be carried out under the direct control of the industries themselves. It is also hoped that the cooperation of the firms concerned in any one industry may enable research work to be undertaken which would not have been dealt with by individual firms.
>
> "All considerations point to the necessity for combination to this end. If the firms in an industry which are engaged in the production of similar articles, or alternatively if the firms in different industries which make use of the

---

[1] "The Government Scheme for Industrial Research," A, Research Association, No. 1. Three other leaflets have been issued to date: No. 2 contains a draft memorandum of association; No. 3 gives the conditions as to the payment of the grant by the Government; and No. 4 discusses the method of subscription to Research Associations.

same or similar raw or semi-manufactured materials will combine to improve those articles or materials, the Department will contribute liberally to a joint fund for this purpose. The fund for each industry will be expended by a Committee or Board appointed by the contributing firms in that industry, and the results obtained will be available for the benefit of the contributing firms.

"The Department realizes that there will be many difficulties in the way. Some industries are more homogeneous in character than others and could therefore agree more easily on the lines of investigation to be followed. Some industries are from their nature only interested in research because they are users of certain materials which are susceptible of improvement, and these materials are also used by other industries. In some cases, accordingly, it may be possible to establish a Research Association for a whole industry, in other only a section may usefully combine, while in still other cases the most likely line of advance may be found in an association of firms in a number of industries which happen to use the same materials. It appears to be certain, however, from these considerations that some firms will wish to belong to more than one combination for research purposes, and that if wasteful effort is to be avoided, every possible means must be used to encourage cooperation between different research organizations as well as between the several firms within the same organization.

"But this will not exhaust the problems ahead. Some firms in an industry will be in a better position to make profitable use of the results of research than others. All firms in an industry are not equally alive to the possibility of improvement, and each individual firm has its own views as regards the measure of the advantage to be obtained from research work in its particular branch of industry.

"All firms invited to join such an organization as is contemplated are likely to ask themselves what they are going to get out of it. They would not be efficient businesses if they did not. The answer to this question ought to give an outline sketch of the way in which such an industrial research organization would work. The means and method of its establishment will be described in later paragraphs.

"It is anticipated that each firm subscribing to a research organization will have the following privileges:

"(1) It will receive a regular service of summarized technical information which will keep it abreast of the technical developments in the industry at home and abroad. To do as much for itself any firm would have to employ more than one man on its staff reading and translating the technical press.

"(2) It will be able to obtain a translated copy of any foreign article in which it may be specially interested and to which its attention will have been drawn by the periodical bulletin.

"(3) It will have the right to put technical questions and to have them answered as fully as possible within the scope of the research organization and its allied associations.

"(4) It will have the right to recommend specific subjects for research, and if the Committee or Board of the research organization of that industry consider the recommendation of sufficient general interest and importance, the research will be carried out without further cost to the firm making the recommendation, and the results will be available to all the firms in the organization.

"(5) It will have the right to the use of any patents or secret processes resulting from all researches undertaken either without payment for licenses, or at any rate on only nominal payment as compared with firms outside the organization.

"(6) It will have the right to ask for a specific piece of research to be undertaken for its sole benefit at cost price, and, if the governing Committee or Board approve, the research will be undertaken.

"It will be realized that no firm outside the organization will have any of these rights. The documents and bulletins available for members of the organization will not be published unless the controlling committee of the organization decide that they shall be.

"The method of assessing the subscription of each firm will have to be determined in negotiation with each industry or section of an industry which may agree to combine for the purposes of research, but the intention is that firms should contribute on a basis proportionate to their size. Thus the small firm will contribute less than the large

> firm, yet it will have the same privileges, though as a rule it will not in the nature of the case have the same facilities for exploiting the results of research. On the other hand the small firm will be more likely to use the benefits offered under heads (3) and (6) than the large firm.
>
> "The Government contribution will be promised for a period of years to be agreed upon, not exceeding five, though it may be extended if funds are available and the condition of the industry calls for further aid. The contribution will be made in the anticipation that when the new organizations are once fairly launched on their career the need for direct State assistance will disappear, and British industry will be as self-sufficing in the field of industrial research as it has proved itself to be in other spheres of work."

The above paragraphs show the broad spirit in which the scheme has been conceived; the breadth of view of the Council is also evident in its remarks upon the constitution of the governing body or council of a trade Research Association. "It is obvious that capital, management and science must have suitable representation. But we believe further that greater success and a wider scope of action will be obtained if provision is made also for the inclusion of labor. In most cases only skilled labor will be concerned. We think it important, however, that the workers in an industry should be able to ascertain at first hand how science is applied to industry and how funds devoted to this purpose are expended, and that they should also be able to urge the importance of research which would result not so much in pecuniary gain as in the increased health and comfort of the workers. . . We believe that (Joint Industrial) Councils[1] so constituted as to be able to discuss with knowledge questions affecting both employers and employed would, if they could be brought to work successfully, greatly help the formation and development of Trade Research Associations."

---

[1] The establishment of which is advocated in the Interim Report of the Sub-Committee of the Reconstruction Committee on Relations between Employers and Employed (Cd. 8606); who propose that such Councils should consider the following among other questions: Industrial research and the full utilization of its results; the provision of facilities for the full consideration and utilization of inventions and improvements designed by workpeople, and for the adequate safeguarding of the rights of the designers of such improvements; improvements of processes, machinery and organization and appropriate questions relating to management and the examination of industrial experiments, with special reference to cooperation in carrying new ideas into effect and full consideration of the workpeople's point of view in relation to them.

Nor is it only from this side that the usefulness of research to labor is recognized; for in the very remarkable report on reconstruction by the sub-committee of the British Labor Party,[1] they write: "From the same source (surplus wealth) must come the greatly increased public provision that the Labor party will insist on being made for scientific investigation and original research, in every branch of knowledge, not to say also for the promotion of music, literature and fine art, which have been under capitalism so greatly neglected, and upon which, so the Labor party holds, any real development of civilization fundamentally depends. . . . Especially in all the complexities of politics in the still undeveloped science of society, the Labor party stands for increased study, for the scientific investigation of each succeeding problem, for the deliberate organization of research, and for a much more rapid dissemination among the whole people of all the science that exists. . . . What the Labor party stands for in all fields of life is, essentially, democratic cooperation; and cooperation involves a common purpose which can be agreed to; a common plan which can be explained and discussed, and such a measure of success in the adaptation of means to ends as will ensure a common satisfaction." All of this reflects a very great change of attitude on the part of both capital and labor, a change which promises well for better relations between labor and capital and for improved conditions generally.

The plan of founding such a Research Association has been under consideration in several industries; the most substantial progress has been made by the cotton industry, a provisional committee of which has worked out a scheme of procedure in considerable detail. They are establishing the British Cotton Research Association that will include as members cotton-spinning and thread-making firms, manufacturers of cloth, lace and hosiery, bleachers, dyers, printers and finishers; it will conduct researches which include the study of the cotton plant at one end and the "finishing" of the manufactured article at the other, and also encourage and improve the education of persons who are, or may be, engaged in the industry. They have published a very interesting pamphlet[1] on "Scientific Research in Relation to Cotton and the Cotton Industry" in which a popular account of the matter is given. It would lead too far to go into this matter; but this report brings out one important point deserving of mention here—namely, with respect to the cost of such research work to each member of the Association. On the basis that the Association would spend $250,000 a year on research work, it is shown that the cost to each member would be only about 10 per cent of his fire insurance premium, 25 per cent of the cost of health insurance, and about 20 per cent of the cost of employers' liability insurance. In other words, the scientific and technical health of the industry can be insured at a very small cost. Indeed this is one of the best ways to look at the matter, namely that research is an insurance, or an amortization of the relative depreciation of the art caused by advances by others and in other directions; and therefore that it is just as proper to consider expenditure on research to be a fixed charge as it is to include charges for insurance or for depreciation.

---

[1] Issued as a supplement to the *New Republic* of February 16, 1918.

The foregoing sketch of the recent development of research, and particularly of cooperative research in Britain, will give some indication of what has been achieved there; though perhaps the most noteworthy point is the changed attitude on the part of manufacturers towards science and education, for without such a change little could have been accomplished. May I add that the general conditions which confronted Britain will soon confront us likewise, if indeed they are not already here; and suggest that their schemes be given careful consideration as being one means of securing greater efficiency in industry and greater economy in the use of our resources of men and materials.[2]

---

[1] Copies obtainable from the Secretary, 108 Deansgate, Manchester; price, ninepence.

[2] This outline of the British scheme is given as an illustration of the importance which the British attach to the question, to show their general plans and to indicate the objects to be attained. It is not implied that we should follow the British procedure in detail; indeed, it is believed that American manufacturers or industrial associations can in general be persuaded to cooperate in industrial research work and to support such work without outside financial aid either from the Government or from other sources.

ORGANIZATION OF INDUSTRIAL RESEARCH.

By Arthur D. Little.[1]

The members of the American Society for Testing Materials are too familiar with the methods and results of research to require explanation of the one or justification of the other. We have long known, as the public at large is beginning to recognize, that research is the prime mover of industry.

During all the years of its existence our Society has been, through its committees and its membership at large, the exponent and practitioner of industrial research. One has only to review the history of a single specification, like that for steel rails, to realize the wide range and splendid quality of research which it connotes and epitomizes.

The war, which has changed everything, has given a new aspect to research. Hereafter the nation which would live must know. Through the wreck and peril of other peoples, Americans have learned with them that research has something more to offer than intellectual satisfactions or material prosperity. It has become a destructive as well as a creative agency and in its sinister phase the only weapon with which it may be fought is more research. The organization and intensive prosecution of research has thus become a fundamental and patriotic duty which can neither be ignored nor set aside without imperilling our national existence.

In considering any plan for the organization of research, one is immediately confronted by the difficulty that science in its highest expression is essentially individualistic and democratic. It resents autocratic control, languishes and becomes sterile under minute oversight and direction from outside. The great advances in human knowledge have almost invariably been due to individual effort set in motion by the scientific imagination and sustained by a consuming desire to ascertain the truth. Pasteur, Curie and Rutherford were not dependent on organization for their results. They worked to the best advantage in proportion as they were free to follow the vision which moved before them. No amount of organization can make a Faraday. It may, perhaps, discover one and is then privileged to provide encouragement, working facilities, and recognition. With these assured it is the part of wisdom to leave him as much alone as possible.

---

[1] President, Arthur D. Little, Inc.

Any really effective plan of research organization must provide for the exceptional man, the man whose angles have not been ground down, who is sometimes not comfortable to rub against, but who has the spark of genius. He is usually a man who hates rules and systems, regular hours, time slips and all the paraphernalia of organization. Organization can help him none the less by relieving him of burdens, making him master of his own time, furnishing equipment, providing organized and immediately available library facilities and by directing his attention to specific problems.

While the superlative work in science, like the superlative work in art, must always be an expression of the genius of the individual and quite beyond the power of organization to ensure, there remains a vast deal of what may be called the secondary work of rounding out the great discoveries and especially of giving them an industrial application which may be rendered most effective only through proper organization. The nimbus which, just at this time, surrounds the word "research" should not blind us to the fact that research involves a great deal of hack work, work for good honest plodders who accumulate the data which permits or confirms the generalization or which is required to give it practical effect.

Broadly stated, the aims of research organization should be:

1. To find, develop and train men.

2. To create such a background in the public mind as shall ensure support for research and the industrial utilization of research results.

3. To secure cooperation between different branches of science, as for example between chemists and mathematicians. The fortuitous combination of the mathematical mind with the viewpoint of the chemist in Willard Gibbs laid the basis for physical chemistry. But such a combination in a single individual is very rare.

4. To avoid repetition and duplication of effort, first by rendering present knowledge readily available to research workers, second by applying clearing house methods to research projects.

5. To stimulate research by emphasizing the importance of specific problems, making special grants, rendering material and facilities as generally available as possible.

6. To furnish a sort of general staff for research which shall work out the plan of attack for major problems, assign the several lines to competent workers and coordinate and focus the whole.

7. To bring home to manufacturers the advantages of research with the view of promoting the establishment of private, corporation, and group laboratories.

8. To make and publish a census of available research facilities in men and equipment.

9. To survey the natural resources of the nation and direct research toward their development.

10. To appraise our great industrial wastes and develop plans and methods for turning them to profitable use.

There is a nearly universal tendency to attempt the accomplishment of these results through the agency of councils and other forms of committee organizations, the members of which are almost without exception unpaid and involved in other activities which have prior claims upon their time. While such systems of organization may be temporarily efficient and even the only ones immediately available in times of sudden crisis, they do not lend themselves effectively to the slow, constructive work of years without which it is impossible to establish research in its proper place in the industrial and other activities of a nation.

There is danger in an organization chart: danger that it be mistaken for an organization.

The work of committees is notoriously cumbersome and slow. The capacity of a committee to achieve results is usually determined by its chairman and is somewhat below his normal working ability as a unit. The reference is of course to executive capacity and ability. In the initial discussion and formulation of plans and policies committees play an essential and most useful part.

As the committee organization is extended to cover the diverging ramifications of a many-phased activity the inherent weakness, for executive purposes, of this form of organization becomes increasingly apparent. More and more power must be developed by the central body to overcome the inertia of the augmented mass. The whole may ultimately break down from its own weight.

It appears then that we may have still to evolve a permanent, coherent and progressively effective form of organization for the promotion and coordination of research. This may perhaps appear in the shape of a great foundation closely affiliated with the government, the universities, the technical societies and the industries, which shall have its broad policies directed by a board, wholly divorced from politics, yet intimately in touch with the trend of science and the needs of industry, and which shall depend for the execution of its plans upon a permanent executive and well-paid scientific staff.

Any permanent research structure of national dimensions must of course have its foundations in the universities and technical schools. Unfortunately in this time of greatest need these institutions are seriously handicapped by the very generosity of their response to the demands already made upon them. In the scientific departments the instructing staff has been heavily drawn upon for special service and those who remain are carrying a greatly increased burden. Students are distracted by war interests and are constantly being diverted into military activities.

While recognizing the exigencies of the period and applauding the splendid response of American institutions of learning, it may not be ungracious or premature to indicate some of the directions in which these institutions must ultimately move if they are finally to meet the augmenting demands for research and for graduates fitted to cope with industrial research problems.

It is beginning to be recognized that there is no valid distinction between scientific research and industrial research. Both employ the same methods and the same equipment.

The demands of either may involve and tax the highest intellectual faculties, and industrial research frequently necessitates that nicety of refinement and subtlety of attack which characterizes the highest scientific effort. There remains only the shifting and uncertain line of demarkation which may indeed be found in motive. In the selection of thesis subjects and minor research problems greater prominence may therefore well be given to those having a direct industrial application.

Industry must, however, continue to look to the higher institutions of learning for the determination of fundamental facts and constants, the development of theory and the establishment of general principles. Any adequate response to this demand requires that professors and assistants should have far more time available for research than is now at their disposal. They must have some substantial measure of relief from routine and administrative detail. They should and undoubtedly will have more direct contact with the industries. As a consequence more and more of them will undoubtedly be drawn into industrial positions. This will mean no ultimate disaster to the cause of scientific education provided university authorities recognize the patent fact that the day has come when much larger salaries must be paid and greater distinction accrue to capable men of science who are to continue as professors. With improvement of status the exceptional men will demand greater freedom of decision and action. They will be less bound by academic system and let us hope that as their capacity for research is demonstrated they will resist the influences which would tend to make them mere administrators.

The expanding recognition of the part which applied science is destined to play in our national development would seem to ensure an adequate supply of scientific students and especially of candidates for degrees in chemistry and chemical engineering. Let us see to it at the start that they are provided with a broader culture than has heretofore obtained in many places, lest they be incapable as scholars of meeting their great responsibilities. Concurrently we must provide means for correcting the recognized deficiencies in their professional training which have been pointed out times without number in the hundreds of papers on the education of the chemist and chemical engineer which have been published during the last few years. Bacon, for example, reports that 70 per cent of the directors of important industrial laboratories express dissatisfaction with the type of instruction which their assistants have received. They find the graduates coming to them ignorant of chemical literature and how to use it, lacking initiative, perspective and sense of proportion, failing in optimism, without knowledge of the simplest industrial equipment. Some of these deficiencies are obviously due to the drying up of inspiration at its source; to the displacement of the quickening influence of master minds by the cut and dried methods of pedagogy. Others, more easy of correction, result from inadequacies of the curriculum itself. It was with the hope of remedying some of the more glaring of these that I made the proposals which led up to the foundation of the School of Chemical Engineering Practice of the Massachusetts Institute of Technology. Recognizing that each process of industrial chemistry may be regarded as nothing more than a coordinated series of unit operations like grinding, roasting, leaching, evaporating, crystallizing and so on, and that knowledge of these unit operations postulates the ability to combine them as required, the school established a number of stations at large industrial plants selected for the variety of unit operations carried out within them. Groups of third-year students passed in turn through each of the stations, studying practice and illustrating theory in the plants themselves. The reaction of the course upon the students went beyond all expectations and it is one of the minor disasters of the war that the school was obliged to suspend by the requisition of its teachers and the diversion of its students into war activities.

We must, however, organize our research with the means and men at hand and look hopefully to the future for accessions of human material of higher average training and far broader scholarship.

Since the frontier of knowledge is the starting point of research the energy of the explorer must be conserved on his way to the frontier. In no way, therefore, can organized cooperation render more effective service to research than by making readily accessible those vast stores of specialized knowledge which research has already accumulated but which still require to be brought into that systematized and orderly arrangement which characterizes science. The research laboratory should be built around a library. These special libraries should be linked together and closely affiliated with the great libraries of the world. Such admirable journals as *Chemical Abstracts* should be substantially endowed, the publication of monographs encouraged and assisted, while systematic reviews and reports of progress covering limited special fields in science and technology should appear far more frequently. The intensive collection of scientific and technical information throughout the world, its codification and its distribution, might well be made a governmental function to an extent not now approached.

Experience has shown that in the organization and conduct of industrial research laboratories certain well-established principles are of general application.

It is desirable that the laboratory be separately housed and that an institutional atmosphere be developed and maintained. It should be recognized that research is necessarily expensive and that results are not forthcoming over night. The ovulation of ideas takes time and their material embodiment proceeds slowly and seldom can be hastened without danger. Adequate equipment, which is often costly, is essential for good work and a liberal policy must be followed where requisitions are concerned. It is well to have the laboratory expenditure arranged on the appropriation system and to allow the director a free hand within the appropriation. If the laboratory is a part of an industrial organization it should maintain close contact through conferences and reports with all departments of the organization; but no department should be allowed to dominate the laboratory, and its director should be responsible only to the executive of the corporation. Since no organization can include every department of human knowledge the director should be encouraged to make frequent use of the advice and services of outside specialists.

"The gods send threads to webs begun," which is the classical way of saying that we have to get into the water to learn to swim. It is, therefore, well in case of major problems to start somewhere as well as may be, even though the starting ground be not wholly to one's liking. It is easily possible to spend too much time in preliminary searches of the literature, and better to avail of early enthusiasms in some initial work at least while carrying on concurrently the tedious task of reviewing and abstracting literature.

Nothing is more expensive or demoralizing than experimentation in the plant. An industrial research laboratory should, therefore, be adequately provided with equipment of semi-commercial size. Infant mortality among processes is high in any case and the most critical period in their young lives is that covering the transition from the laboratory to the plant. They require and the research laboratory should provide a nursery to protect and foster them during this period of their development. Some large manufacturers have even found it desirable to operate in connection with and under the sole direction of their research laboratory a small plant in which actual commercial manufacture is regularly conducted. Such extension of the laboratory's function permits the complete reduction to practice of new methods and the commercial demonstration of the sufficiency of the product before the innovations are introduced into the main plant.

Even when no such provision appears feasible it is, nevertheless, highly desirable to have the industrial research laboratory actually engaged in some small scale, highly specialized, commercial manufacture, preferably of some product which it has itself originated. The least advantage of this procedure is that such manufacture of a properly selected product may frequently defray a substantial proportion of the expenses of the laboratory. The major benefits are the acquirement of a certain commercial sense by the laboratory staff, an appreciation of the conditions and difficulties of actual production, and finally the strengthening of the position of the laboratory through the increase in its turn-over and equipment. Such procedure, while perhaps not general, has been followed to great advantage by the research laboratories of the General Electric Co., the Eastman Kodak Co. and Arthur D. Little, Inc.

As regards any research laboratory, it goes without saying that it is the personal factor which determines performance and this is preeminently true of the laboratory director. Sir Humphrey Davy truly said that his greatest discovery was Michael Faraday, and no greater problem is likely to confront a research laboratory than that involved in the discovery of a director. Successful laboratory directors may be of several types, but a militant optimism, contagious enthusiasm, controlled imagination and quick human sympathy are common to them all. Such a man will naturally in selecting his subordinates look for these personal qualities almost as carefully as he will weigh specialized scientific training, and having been thus guided in his selections will find it relatively easy to inspire throughout his organization those relations of good fellowship and that *esprit de corps* which multiply enormously the effectiveness of any working force.

Exceptional men are hard to find simply because they are exceptional, and the director in laying out the work of the laboratory and extending its personnel will endeavor to augment the output of the exceptional man through the coordinated effort of properly directed men of secondary capacity.

Fairness in apportioning credit, frequent conferences, and opportunity for self-development are essential to the attainment of high efficiency.

Among laboratories thus constituted and directed, cooperation should not be difficult and is, in fact, already frequent. The real need of the situation is cooperation among manufacturers for the support of research. The long first steps in this direction have already been taken in Great Britain by the Advisory Council for Scientific and Industrial Research. In our own country the National Canners Association has been signally successful in applying to research the principle of cooperation. We shall to-night, most fortunately, be authoritatively informed regarding each of these developments. Stimulating and encouraging as they are, we must, nevertheless, regard them only as surface indications of the great wealth of opportunity which lies below. There is hardly a trade association in the United States which might not to the great advantage and profit of its members address itself to the solution of common problems by similar means.

All manufacturers of yellow pine are, for example, vitally interested in the utilization of wood waste. The paper makers of the country have a common interest in finding new sources of paper stock. The sugar growers have it in their power to put new values in molasses, and it is easy to conceive that a tax of one per cent on natural gas production, if properly applied to research, might be as fruitful in result as that research by Frasch which boomed Ohio oil from 19 cents to $1.10 per barrel.

Where the opportunity and benefit is so obvious and results so reasonably assured, it is unfortunate that producers generally should be so prone to rely upon governmental agencies for efforts which they might far better make themselves. The natural place for industrial research is in the laboratories controlled or supported by individual corporations, or which are otherwise for the time being working in their interest, or else in group laboratories maintained by trade associations for the common benefit of their membership. It can only be established firmly on a basis which recognizes that people are in business to make money and that for the long pull personal interest must be enlisted. Those of us, therefore, who believe that every waste that is prevented or turned to profit, every specification which gives better control of raw material, every problem solved, and every more effective process which is developed makes for better living in the material sense and for cleaner and more wholesome living in the higher sense, can render no more effective service than by aiding the American manufacturer to understand what research is, what it costs, why it pays.

DEVELOPMENTS IN INDUSTRIAL RESEARCH.

By Charles L. Reese.[1]

I have been asked to speak, as far as possible, of successful experiences in the practical application of industrial research. Instead of attempting to cover in the short time available the very wide field of chemical research, I am taking the liberty of confining my observations to research developments in one large industrial corporation, as I have been in close personal contact with these developments, and, therefore, am in a better position to make accurate statements than I would be if I attempted a more general discussion.

The du Pont Company started its research department June 1, 1902, by establishing what is known as the Eastern Laboratory, at Gibbstown, N. J. A force of five chemists, including the director, constituted its personnel. The director's duties were two-fold: first, directing laboratory research work, and second, studying chemical operations of the high explosives plants.

In 1903 a second experimental laboratory, known as the Experimental Station, was established in Wilmington to handle work specifically for the development department of the company. This was later extended to include also work in connection with the manufacture of black and smokeless powder.

In 1912, the Delta Laboratory was established for the purpose of investigating problems in connection with the manufacture of pyralin or celluloid, and in 1917 the Jackson Laboratory was established in connection with the dyes industry. All these experimental laboratories were placed either at, or in close proximity to manufacturing plants, in order to facilitate the study of plant problems.

Very soon after the establishment of the Eastern Laboratory, it was found desirable to have a head of the research department at the main office in Wilmington, Del., where the du Pont

---

[1] Chemical Director, E. I. duPont de Nemours and Co.

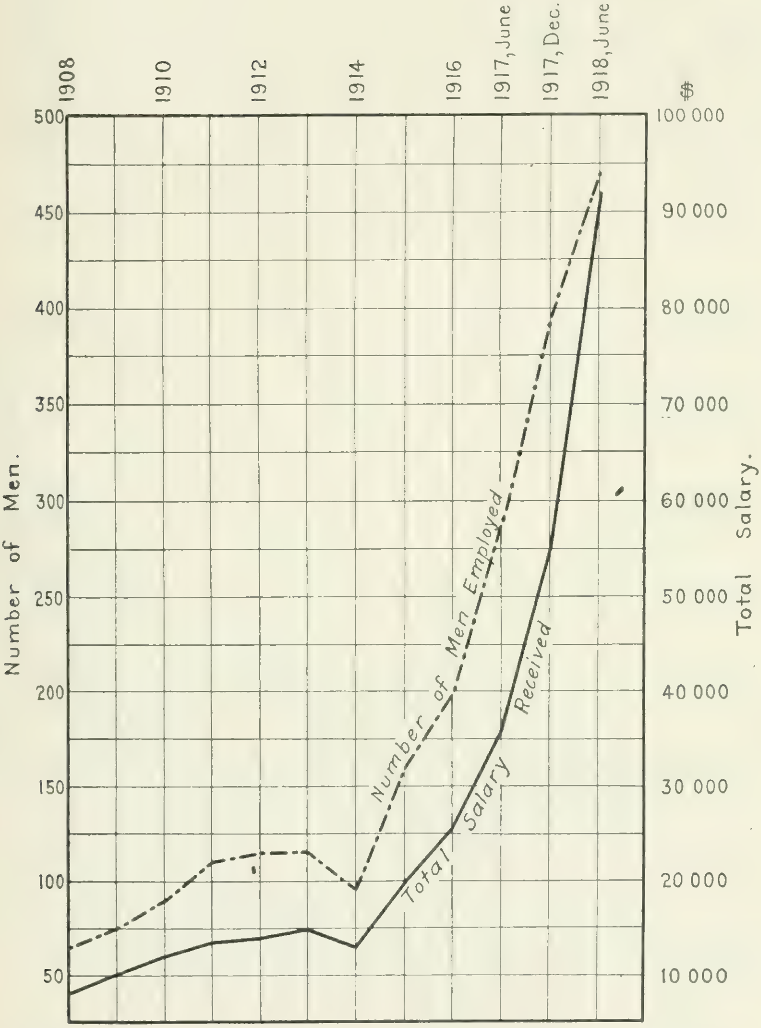


FIG. 1.—Curves Showing the Number of Men Employed in Research by the du Pont Company, and Their Total Salary for the Last Ten Years.

Company's executive work is centralized, in order to provide a clearing house for the several research laboratories, and to have available a force of expert chemists, who could not only keep in touch with actual manufacturing operations at the various plants, but who could act in a consulting capacity to the various departments. At the same time it was found advisable to centralize all chemical research work under one chemical director, and accordingly the experimental station, which had been connected with the development department, became a part of the chemical department organization.

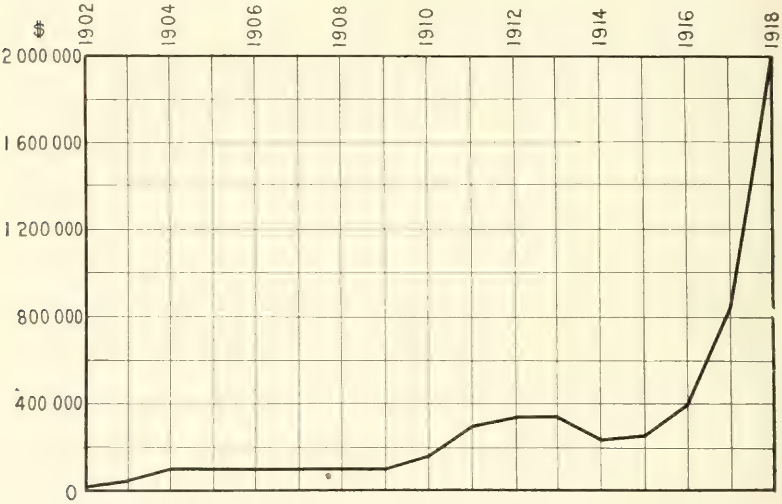


FIG. 2.—Curve of Increase in Expenditure for Research Work by the du Pont Company during the Period 1902–1918.

The growth of the research activities since the establishment of the Eastern Laboratory in 1902 is well illustrated by Fig. 1, which shows the number of salaried employes, and the salaries paid per month during the last ten years.

Not only has the number of salaried employes increased considerably during these ten years, but the salary rates have very decidedly increased, although this is not true of the average per man, due to the increased proportion of younger men employed in the last few years. Furthermore, as will be seen

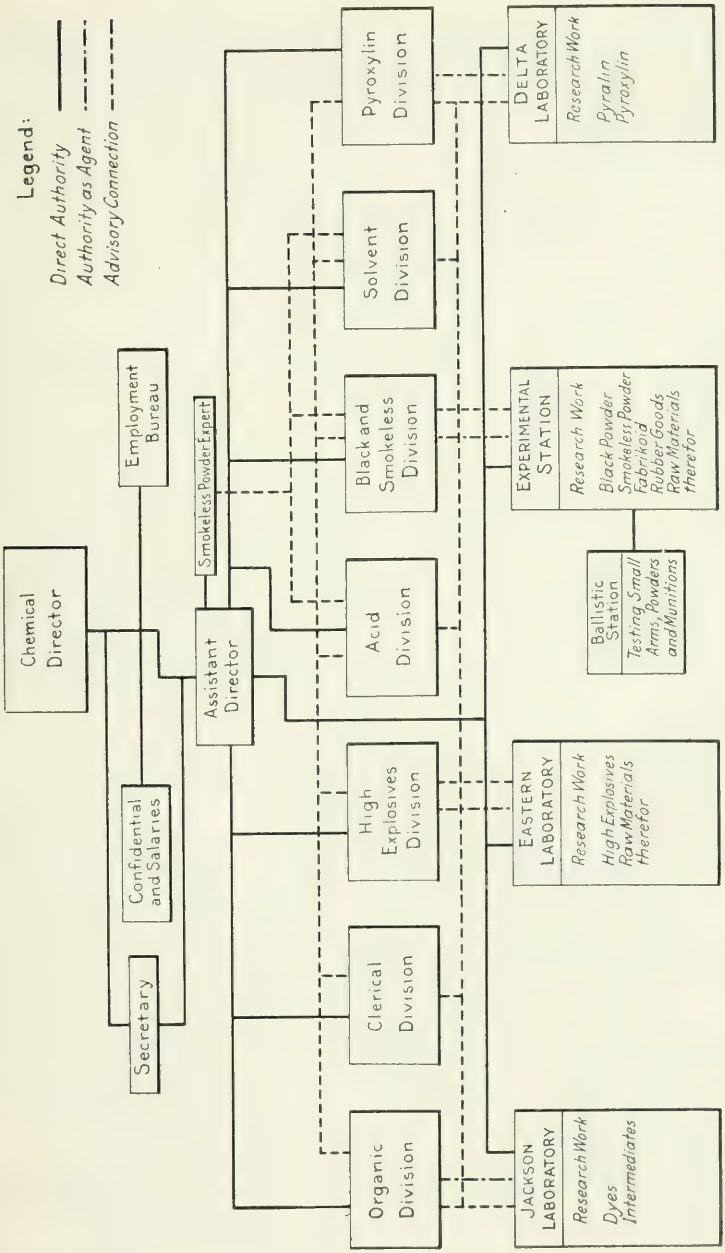


FIG. 3.—Organization Layout of Chemical Department of the du Pont Company

from Fig. 2, the total yearly expenditures for research work have grown from fifty thousand to two million dollars. This growth in research activity shows clearly that the du Pont Company considers its research department a distinctly profitable undertaking.

During the period from 1912 to 1915, the total expenditures for research work amounted to approximately $1,200,000, while the total savings, direct or indirect, accomplished by this expenditure were $14,000,000. It is, of course, difficult—in fact almost impossible to calculate the exact pecuniary saving brought about by many lines of research, but the above figures, which represent only savings which could definitely be traced to research activities, give some idea of the magnitude of what can be accomplished.

Fig. 3 shows the present organization of the chemical department of the du Pont Company. In addition to the chemical force, which is directly engaged in research work, and which is represented by the chemical department with its several branches, the company employs a large number of graduate chemists in its various plants, either in plant laboratory work, or in the supervision of its chemical manufacturing operations. The total number of chemists employed at present, including those in the research department, is approximately 1100.

The first important problem undertaken by the research department when established, was a study of a difficulty met with in works operations, in the separation of nitro-glycerin from waste nitrating acid. After a few months' study this problem was solved by the discovery of the presence of colloided silica in certain brands of glycerin, which hindered the separation of the nitro-glycerin from the acid. It was found that by the addition of minute quantities of sodium fluoride, the separation could be reduced from a period as long as two hours to one of a few minutes. By this reduction in the time of separation, an enormous saving in time and cost of manufacture was accomplished, and the research department received immediate recognition.

From the first beginning to the present time, progress in research has been like a triumphal procession. Investigations of existing manufacturing processes led to changes in the manufacture of nitro-glycerin, nitric acid, sulfuric acid, ammonium nitrate, all of which are raw materials used in the manufacture of dynamite; likewise nitro-cellulose and ether used in smokeless powder manufacture and acid and solvent recovery. As a result we have been enabled to obtain practically theoretical chemical yields in the manufacture of these products, and by improvements in machinery, equipment, methods of handling and by substitution of mechanical processes for labor, have accomplished savings of millions of pounds of raw materials and a corresponding monetary saving.

I wish to mention several developments which have occurred since the beginning of the war, and which will contribute in no small measure to a final successful end of it.

In 1914, when the British embargo cut off the supply of German potash salts, the du Pont Company was in a position to undertake the immediate production of potash salts from its nitrate deposits in Chile, as the research department had already discovered the presence of these salts in these deposits, and had developed a satisfactory method for their extraction. This achievement not only assists in helping to meet the shortage of potash salts, but insures a supply for the manufacture of black ignition powder, which is absolutely necessary for igniting and firing charges of smokeless powder in our large guns.

A threatened shortage in the supply of sheet lead, an actual shortage of lead burners and the necessity for a tremendous increase in the production of sulfuric acid for the manufacture of explosives, made it imperative to find a substitute for lead in the construction of sulfuric acid plants. This problem was solved satisfactorily, and to-day millions of pounds of sulfuric acid are being manufactured in plants which have not a pound of lead in their construction.

The problems of the manufacture of diphenylamine—a necessary ingredient in smokeless powder which prevents its deterioration—and of the raw material, aniline, used in the manufacture of diphenylamine, were quickly and satisfactorily solved in American research laboratories, and this ingredient, which was obtainable in large quantities from Germany only, is now manufactured in this country, at a rate of thousands of pounds per day.

While these developments and achievements illustrate what has been done in the way of supplying requirements, or furnishing substitutes for raw materials difficult or impossible to obtain, the accomplishments in the field of conservation of material have been as great, if not greater. I wish to mention here two which, from the standpoint of magnitude, are well worth recording. In the manufacture of the type of powder employed by the United States Army, and now largely employed by the Allies in Europe, large quantities of alcohol and ether solvent are required. On account of the volatility of both of these substances, large losses take place during the manufacture of powder. By studying carefully these losses in the place where they occur, changes in manufacturing operations were made possible which enabled us to save solvent, which, under the present scale of manufacture of powder, would amount to some fifty million pounds per year. Likewise, in the manufacture of guncotton, where large quantities of nitric acid were lost several years ago, we have been enabled by careful study to make changes which have accomplished a saving equivalent to some forty-five million pounds of nitric acid a year. When you remember that heretofore nitric acid has been manufactured almost entirely from Chile saltpeter, and that the scarcity of shipping has made it difficult to maintain an adequate supply of this material, which is so essential for the successful raising of large crops, you will realize what the chemical research of this one company alone has been able to contribute to the successful termination of the war, aside from and in addition to the production of actual military explosives.

Before the United States entered the war, the demand for toluol became so great, and the price so high, that two distinct methods for the synthetic manufacture of this material were developed. Two methods for the manufacture of picric acid were also developed and operated satisfactorily.

There is a high explosive used for primers in military explosives, as well as in blasting caps, known as tetryl, or tetranitromethylaniline. Processes for the manufacture of tetryl and dimethyl-aniline were developed and put into satisfactory operation.

Owing to the very large program for high explosives after the United States entered the war, it became necessary to develop other high explosives than trinitro-toluol, picric acid and ammonium nitrate, and within a very short period the research department developed four new high explosive materials, all of which have been adopted by the Government, and will materially relieve the situation as regards shortage of these materials. I am very sorry that I am unable to give you any details relative to their composition, but I will mention them as follows:

Trinitro-xylol;
Lyconnite, to be used in aerial bombs;
Starite, to be used in aerial bombs and trench mortar shells;
Grenite, to be used in hand grenades

It is hardly necessary to bring to your attention the developments carried on by the research laboratories, not only of the du Pont Company, but of a large number of other concerns, which have resulted in a very satisfactory solution of the dyes situation in this country. This will in short order enable the dyes industry to produce all the important dye which we were of necessity importing from Germany before the war.

If I had the time available I could not only multiply these instances from the experiences of one company, but could extend my list to accomplishments of every large industrial corporation that maintains an adequate staff of research chemists. As it is, I have only been able to indicate to you the general trend toward increased amount of research work as evidenced by the expansion which has taken place in the du Pont Company as only one instance of many, and I have indicated to you the possibilities in saving, in conservation of resources, and in increasing efficiency, which can be accomplished by systematized and well-organized research work.

COOPERATIVE RESEARCH IN THE AMERICAN CANNING INDUSTRY.

By Frank E. Gorrell.[1]

The National Canners Association began to think of cooperative research about eight years ago. In 1910 the need of definite information regarding tin plate developed. To study this question an experimental pack was put up which was examined periodically by the Institute of Industrial Research and also by the Bureau of Chemistry and the Chemical Laboratory of the American Can Company. This investigation was completed in 1913. In the meantime, the need of research along broader lines had developed and it was found desirable to have scientific men giving their entire time to the problems of the industry. The result was the organization of the Research Laboratories of the National Canners Association in the summer of 1913.

The problems these laboratories have studied in the main have related to difficulties of the canning industry. These difficulties are of the most diverse character. Among them are spoilage, faulty color of food, imperfections in the container, and defective machinery. The ordinary operations of canning must sometimes be altered because of special conditions. The raw product occasionally has some characteristic (not noticeable when cooked in the kitchen) which necessitates special treatment when the product is canned.

These difficulties are only occasional. A plant may be operated for years without experiencing one of them. In one plant the cause of a certain difficulty may be obscure; in another, obvious. Most canning plants are small and are only operated for a few weeks of the year. A laboratory for each would be impracticable, wasteful, and necessarily inefficient. On the other hand, a central laboratory is able to study these difficulties as they arise at one plant after another and thus sometimes get a broader view and reach more reliable conclusions than would be possible in a single plant.

---

[1] Secretary, National Canners Association.

Thus far the attention of the laboratory has been devoted in the main to everyday problems and difficulties of the canning industry. Some of these problems have been solved in a satisfactory way; others are still being studied. Some investigations of a more fundamental character are under way and material progress has been made. Not the least important feature of the laboratory is in holding before the members of the Association at all times the importance of submitting to careful investigation all problems relating to the industry. In this manner they unconsciously learn to attach greater value to industrial research.

In addition to their own work, the laboratories are of value in correlating the work of other organizations and in assisting other laboratories to find locations and conditions in which problems may be studied. For instance, something like three years ago, the laboratories planned a study of methods for the disposal of liquid wastes from some types of canning plants. On looking into the matter it was found that the laboratory of the Public Health Service was interested in the same question from the standpoint of the protection of the water supplies. Our laboratories were able to bring to the attention of the Public Health Service locations presenting conditions in which the problem could be studied advantageously.

In addition to the Research Laboratories just referred to, the canning industry maintains research work in connection with the inspection of canned foods. During the last two years three sections of the National Canners Association have put their plants under inspection, financed by them but controlled by the National Canners Association. This inspection is maintained for the purpose of controlling the character of the raw material and the sanitation of the plants, and considerable research work has been found necessary in connection with it.

For a long time, food manufacturers have felt the need of an exhaustive study of food poisoning, more commonly known as "ptomaine poisoning." The canning industry decided to finance such an investigation, but experienced some difficulty in making arrangements to have it conducted under the most advantageous auspices. Finally, at the request of the National Canners Association, the National Research Council organized the investigation, naming as the Director Dr. M. J. Rosenau, head of the Department of Preventive Medicine and Hygiene of Harvard Medical School, and also naming an Advisory Board consisting of six of the most eminent scientific men in the country. None of these men could have been secured for this investigation by the industry itself. They appreciated the importance of the study as a public measure, however, and accepted the invitation of the National Research Council to do the work. It is well known that our information on food poisoning is only fragmentary and unreliable. We hope this investigation will secure information of a fundamental nature.

As our work progresses the importance of research work is becoming more strongly impressed on our members. In the canning industry the individual plants are small and there are many general problems which can only be studied in a cooperative way.

DEVELOPMENT OF EXISTING AGENCIES.

By Alfred D. Flinn.[1]

Centralized agencies exist for promoting industrial research and carrying on all its branches. Some have but recently been created, while others have a number of years of history. To coordinate, expand, perfect and strengthen these agencies is the task of the hour rather than to create new organizations. These bodies for centralized activity in research in applied science are the National Research Council, established by the National Academy of Sciences on the request and by the authority of the President of the United States; United Engineering Society, with its subsidiaries, the Engineering Foundation and Engineering Societies Library, backed by the great national societies of professional engineers; and the Government bureaus engaged in research. All these bodies are now coordinated and cooperating to some degree, but their relationships should be much more clearly defined and firmly established. With them must be suitably connected the research departments of universities and industrial establishments. The next steps in behalf of the central agencies are greatly to increase their resources in funds, trained men and equipment, and to make known to the industries, to national and state governmental departments, and to the public, their existence, their readiness to serve, their needs, and the inestimable benefits the country and to the world which can be achieved through them.

An instrument for collecting, classifying, organizing and disseminating recorded scientific knowledge in all forms exists in healthy embryo in the Engineering Societies Library with its 140,000 volumes. It needs large additional funds at once to perfect the cataloging of material in hand and constantly being received, and to inaugurate other activities, chief among which should be the creation of a great card catalog of scientific literature, both pure and applied, which shall excel that of the German government, esteemed more valuable than the wonderful laboratory at Grosslichtefelde with which it is connected. Such a card catalog should be begun without delay, for the task of compilation is gigantic; but the constantly growing intangible loss without it far exceeds its cost. It has been stated that 80 per cent of the problems sent to the Grosslichtefelde laboratories are answered by the card catalog quickly, without expenditure of money and time for research work in the laboratories. As a conservator of time and of resources of all kinds, the Library, if properly developed, would be the greatest single factor in industrial and all other research. Its development as an active agency in technical research, and not merely as a collection of books, should go forward at once. Other scientific libraries and the technological departments of public libraries, including libraries in universities and technical schools, should be linked with this great central engineering library, which is already the largest technical library in the Western Hemisphere and one of the most important in all the world.

---

[1] Secretary, United Engineering Society, Engineering Foundation, Engineering Council, and Assistant Secretary, National Research Council; formerly Deputy Chief Engineer, Catskill Aqueduct, New York.

The Engineering Foundation is cooperating with the National Research Council in promoting industrial research. It could also occupy a large and distinct portion of the field of research namely the establishment and supervision of great general engineering laboratories at two or three places in the country, in which could be investigated engineering problems of public character, or too large for private laboratories, or having no immediate possibility of commercial rewards sufficient to enlist the support of private capital. There are many important problems, worthy of investigation, of a strictly engineering character (in contrast to commercial manufacturing) which could be assigned to such laboratories without duplicating work being done in government, state and other existing laboratories.

Another great function for Engineering Foundation would be determining and publishing of engineering standards through the adoption of the American Engineering Standards Committee as a division of the Engineering Foundation. This committee has long been in process of organization by the

American Society of Civil Engineers, American Institute of Mining Engineers, American Society of Mechanical Engineers, American Institute of Electrical Engineers and the American Society for Testing Materials, and still lacks a suitable effective connection with the centralized activities of the profession. Instead of creating a new separate organization, this committee might well be adopted and fostered by the Engineering Foundation. Since the committee's work would be purely technical, it would be incorporated in the Foundation rather than the Engineering Council, the province of which is to deal with non-technical matters of common concern to engineers in all branches of the profession. Furthermore, this matter of standards would most fittingly combine with the management of the engineering research laboratories just proposed.

One other feature of the great centralized scheme should be mentioned, namely, a medium of communication through which the Library and laboratories could periodically convey results to the societies, to the profession and to the public. No private publication could meet the requirements, for such a journal must be wholly free from commercial bias in the determination of its policies, the statement of facts and the expression of opinion. United Engineering Society, as the business corporation of the centralized activities of the engineering profession, could properly undertake the creation of a publication board for this research journal. Whether issued weekly or monthly, and whether made self-supporting by subscriptions and advertisements or otherwise maintained, are questions for later decision. The necessity for such a publication is beyond dispute.

Besides the great engineering societies and other central organizations which have been named, there are other agencies in the field of industrial research which should be conserved and utilized. In his combined cooperative capacity as Secretary of Engineering Foundation, Assistant Secretary of the National Research Council and member of the Industrial Research Section of the latter, the writer has been collecting names of industrial research laboratories. From a number of correspondents a list of nearly three hundred and fifty laboratories in America said to belong to this class has been obtained. No pretense to completeness can be made for this list. Although the names of some laboratories known to be engaged in commercial testing rather than in research have been eliminated, it is mistrusted that the list has not yet been wholly purged. No disparagement is intended to this very useful class of laboratories and there are probably numerous laboratories which combine commercial testing with more or less of genuine research work. It is desired to prepare a list of those industrial laboratories which are engaged in systematic investigation of scientific phenomena or engineering applications of science for the purpose of adding to human knowledge, and to collect information concerning them which will make possible their articulation with the plan for industrial research being developed by the National Research Council and the Engineering Foundation to embrace all the industries of the country.

It has occurred to the writer that publication by the American Society for Testing Materials of the names already gathered may not only be helpful toward the perfecting of a list and the securing of the additional knowledge sought, but also may have no small usefulness even in its present imperfect form. Readers are therefore requested to aid, if they conveniently can. It is proposed to mail this printed statement to each laboratory named, requesting a brief outline of its equipment, the research problems in hand or completed, the general nature of the field to which it restricts its work, the number of trained research men on its staff, the proportion of time spent in genuine research, and the possibility of undertaking other research work. Information thus gathered will be for the joint use of the National Research Council and the Engineering Foundation.

LABORATORIES ENGAGED IN INDUSTRIAL RESEARCH, PARTLY OR WHOLLY.

(A Tentative List; Corrections Requested.)

Note:—Government and university laboratories have been omitted.

Abbott Laboratories, Chicago, Ill.
Advance Rumely Co., La Porte, Ind.
Aetna Chemical Co., Carnegie, Pa.
Air Reduction Co., New York City.
Alexander Brothers, Philadelphia, Pa.
Aluminum Castings Co., Cleveland, O.
Aluminum Co. of America, New Kensington, Pa.
American Agricultural Chemical Co., New York City.
American Association of Woolen and Worsted Mfrs., New York City.
American Beet Sugar Co., New York City.
American Brass Co., Waterbury, Conn.
American Bureau of Inspection and Tests, Chicago, Ill
American Can Co., New York City.
American Cyanamid Co., New York City.
American Development and Operating Co., Chicago, Ill.
American Gas Institute, Philadelphia, Pa.
American Glue Co., Peabody, Mass.
American Leather Research Laboratory, New York City.
American Locomotive Co., Schenectady, N. Y.
American Optical Co., Southbridge, Mass.
American Paper and Pulp Mfrs. Association, New York City.
American Platinum Works, Newark, N. J.
American Rolling Mill Co., Middletown, O.
American Sheet and Tin Plate Co., Pittsburgh, Pa.
American Smelting and Refining Co., New York City.
American Steel and Wire Co., Waukegan, Ill.
American Sugar Refining Co., New York City.
American Tar Products Co., Chicago, Ill.
American Telephone and Telegraph Co., New York City
American Window Glass Co., Pittsburgh, Pa.
American Writing Paper Co., Holyoke, Mass.
American Zinc, Lead and Smelting Co., St. Louis, Mo.
Amoskeag Mfg. Co., Manchester, N. H.
Anaconda Copper Mining Co., Anaconda, Montana.
Arbuckle Brothers, Chicago, Ill.
Arlington Mills, Lawrence, Mass.
Armour and Co., Union Stock Yards, Chicago, Ill.
Armour Fertilizer Works, Chicago, Ill.
Armour Glue Works, Chicago, Ill.
Art in Buttons Co., Inc., Rochester, N. Y.
Association of Metal Lath Mfrs., Cleveland, O.
Atlantic Refining Co., Philadelphia, Pa.

Babcock and Wilcox Co., Bayonne, N. J.
Baker and Adamson Chemical Co., Easton, Pa.
Baker Chemical Co., J. T., Phillipsburgh, N. J.
Baldwin Locomotive Works, Philadelphia, Pa.
Barber Asphalt Paving Co., Maurer, N. J.
Barber-Colman Co., Rockford, Ill.
Barrett Co., The, New York City.
Bartlesville Zinc Co., Bartlesville, Okla.
Bausch and Lomb, Rochester, N. Y.
Beckman and Linden, Inc., San Francisco, Cal.
Belden Mfg. Co., The, Chicago, Ill.
Benzol Products Co., Marcus Hook, Pa.
Berlin Mills Co., Portland, Me.
Bethlehem Steel Co., S. Bethlehem, Pa.
Biddle, James G., Philadelphia, Pa.
Bogardus Testing Laboratories, Seattle, Wash.
Boonton Rubber Mfg. Co., Boonton, N. J.
Boston Bi-Chemical Laboratory, Boston, Mass.
Boston Woven Hose and Rubber Co., Cambridge, Mass.
Bowker Fertilizer Co., Boston, Mass.
Boynton Oil and Gas Co., Muskogee, Okla.
Brach and Sons, E. J., Chicago, Ill.
Brewers and Distillers Laboratories, Chicago, Ill.
Bridgeman Russell Co., Duluth, Minn.
Brown and Sharpe, Providence, R. I.
Buckeye Clay Pot Co., Toledo, O.
Buda Co., Harvey, Ill.
Buick Automobile Co., Flint, Mich.
Burdett Mfg. Co., Chicago, Ill.
Burgess Battery Co., Madison, Wis.
Burgess Co., The, Marblehead, Mass.
Burke and James, Inc., Chicago, Ill.
By-Products Coke Corp., South Chicago, Ill.
Byron Weston and Co., Dalton, Mass

Cambria Steel Co., Johnstown, Pa.
Carnegie Steel Co., Pittsburgh, Pa.
Carus Chemical Co., La Salle, Ill.
Caulk Dental Co., L. D., Milford, Del.
Chalmers Automobile Co., Detroit, Mich.
Champion Spark Plug Co., Flint, Mich.
Chemical Paper Co., Holyoke, Mass.
Clark Equipment Co., Buchanan, Mich.
Cleveland Cliffs Iron Co., Ishpeming, Mich.
Coal Products Mfg. Co., Aurora, Ill.
Colgate and Co., Jersey City, N. J.
Colorado Fuel and Iron Co., Denver, Col.

Columbia Graphaphone Co., Bridgeport, Conn.
Commercial Research Co., Flushing, L. I.
Commonwealth Edison Co., Chicago, Ill.
Comstock, Kahms and Westcott, Industrial Research Laboratory, Boston, Mass.
Corn Products Co., Edgewater, N. J.
Corning Glass Works, Corning, N. Y.
Corona Chemical Co., Milwaukee, Wis.
Cosden and Co., Tulsa, Okla.
Cramer Dry Plate Co., St. Louis, Mo.
Cramp and Sons, Wm., Ship and Engine Building Co., Philadelphia, Pa.
Crane and Co., Dalton, Mass.
Crocker-McElwain Co., Holyoke, Mass.
Crucible Steel Co., Pittsburgh, Pa.
Cudahy Packing Co., Chicago, Ill.
Curtis Aeroplane and Motor Co., Buffalo, N. Y.
Cutler-Hammer Mfg. Co., Milwaukee, Wis.

Darling and Co., Chicago, Ill.
Dayton Engineering Laboratories Co., Dayton, O.
Dearborn Drug and Chemical Co., Chicago, Ill.
De Laval Steam Turbine Co., Trenton, N. J.
Detroit Edison Co., Detroit, Mich.
Diamond Match Co., Oswego, N. Y.
Dietzgen, Eugene, Chicago, Ill.
Dodge Bros., Detroit, Mich.
Doehler Die Casting Co., Brooklyn, N. Y.
Dow Chemical Co., Midland, Mich.
Drackett and Sons Co., P. W., Cincinnati, O.
du Pont de Nemours Co., E. I., Wilmington, Del.

Eagle and Biological Supply Co., Kansas City, Kan.
Eastern Mfg. Co., Bangor, Me.
Eastman Kodak Co., Rochester, N. Y.
Edison, Inc., Thomas A., West Orange, N. J.
Edison Electric Illuminating Co., Boston, Mass.
Edison Phonograph Works, Orange, N. J.
Eimer and Amend, New York City.
Ele Kem Co., Chicago, Ill.
Electrical Testing Laboratories, New York City.
Elgin Watch Co., Elgin, Ill.
Eli Lilly and Co., Indianapolis, Ind.
Elk Tanning Co., Laboratory, Ridgeway, Pa.
Ellis Foster Co., Montclair, N. J.
Emerson Laboratory, The, Springfield, Mass.
Emery, A. J., Stamford, Conn.
Empire Gas and Fuel Co., Bartlesville, Okla.
Euclid Glass Div., National Lamp Works, Cleveland, O.

Fairbanks Co., N. K., Chicago, Ill.
Federal Dye-Stuff and Chemical Corp., Kingsport, Tenn.
Fire Underwriters Laboratories, Chicago, Ill.
Firestone Tire and Rubber Co., Akron, O.
Fisher Body Corps., Detroit, Mich.
Ford Automobile Co., Detroit, Mich.
Ford and Son, Henry, Dearborn, Mich.
Foy Glass Co., H. C., Rochester, Pa.
Frink Pyrometer Co., Lancaster, O.
Fulton Bag and Cotton Mills, Atlanta, Ga.

Gallum and Sons Co., A. F., Milwaukee, Wis.
Gas Distribution Consolidated Gas, Elec. Light and Power Co., Baltimore, Md.
General Aeroplane Co., Detroit, Mich.
General Bakelite Co., New York City.
General Chemical Co., New York City.
General Electric Co., Lynn, Mass.
General Electric Co., Pittsfield, Mass.
General Electric Co., Schenectady, N. Y.
General Motors Co., Detroit, Mich.
Gillette Safety Razor Co., Boston, Mass.
Glenn-Martin Aircraft Co., Cleveland, O.
Goodrich Co., B. F., Akron, O.
Goodyear Tire and Rubber Co., Akron, O.
Grasselli Chemical Co., Cleveland, O.
Great Western Sugar Co., Denver, Col.
Gulf Pipe Line Co., Houston, Texas.
Gulf Refining Co., Pittsburgh, Pa.
Gulf Refining Co., Port Arthur, Texas.
Gulick Henderson Co., Chicago, Ill.
Gundlack Optical Co., New York City.
Gurley and Co., Troy, N. Y.
Gypsum Industries Association, New York City.

Hall-Scott Motor Car Co., San Francisco, Cal.
Hampden Glazed Paper Co., Holyoke, Mass.
Harbison-Wallser Refractories Co., Philadelphia, Pa.
Hardware Lumber Association, New York City.
Haynes Automobile Co., Kokomo, Ind.
Hercules Powder Co., Wilmington, Del.
Hershey Chocolate Co., Hershey, Pa.
Hess-Bright Mfg. Co., Philadelphia, Pa.
Hoffman Oil and Refining Corp., Houston, Texas.
Holland Aniline Co., Holland, Mich.
Hollow Building Tile Association, Chicago, Ill.
Hooker Electrochemical Co., Niagara Falls, N. Y.
Hord Color Products Co., Sandusky, O.

Huasteca Petroleum Co., New Orleans, La.
Hudson Automobile Co., Detroit, Mich.

Illinois Steel Co., South Chicago, Ill.
Illinois Watch Case Co., Elgin, Ill.
Industrial Alcohol Co., New York City.
Industrial Chemical Co., Milwaukee, Wis.
Ingersoll-Rand Co., New York City.
Inland Steel Co., Indiana Harbor, Ind.
Institute of Industrial Research, Washington, D. C.
International Acheson Graphite Co., Niagara Falls, N. Y.
International Harvester Co. of N. J., Chicago, Ill.
International Nickel Co., New York City.
International Silver Co., Meriden, Conn.

Jeffery-Dewitt Co., Detroit, Mich.
Jobbins, Wm. F., Inc., Aurora, Ill.

Karpen and Brother, S., Chicago, Ill.
Kellogg Switchboard and Supply Co., Chicago, Ill.
Keuffel and Esser Co., Hoboken, N. J.
Kistler Lesh and Co., Morgantown, N. C.
Klipstein and Sons Co., E. C., South Charleston, W. Va.
Koppers Co., Pittsburgh, Pa.

Lackawanna Steel Co., Buffalo, N. Y.
Lake Superior Paper Co., Ontario, Canada.
Lazell, E. W., Portland, Ore.
Leeds and Northrup Co., Philadelphia, Pa.
Lewis Mfg. Co., F. J., Chicago, Ill.
Lincoln Co., E. S., Waterville, Me.
Linde Air Products Co., New York City.
Lindsay Light Co., Chicago, Ill.
Little, Arthur D., Inc., Boston, Mass.
Lock Brothers, New York City.
Longyear-Michigan Exploring Co., Marquette, Mich.
Ludlum Steel Co., Albany, N. Y.
Lumen Bearing Co., Buffalo, N. Y.
Lunkenheimer Co., Cincinnati, O.

Magnus Metal Co., Chicago, Ill.
Mallinckrodt Chemical Works, St. Louis, Mo.
Mantle Lamp Co. of America, Chicago, Ill.
Marland Refining Co., Ponca City, Okla.
Mayo Foundation, Rochester, Minn.
McKinney Steel Co., Cleveland, O.
Medina Gas and Fuel Co., Wooster, O.
Mellon Institute, Pittsburgh, Pa.

Midvale Steel Co., Philadelphia, Pa.
Miller Rubber Co., Akron, O.
Minneapolis Steel and Machinery Co., Minneapolis, Minn.
Mishawaka Woolen Mfg. Co., Mishawaka, Ind.
Monsanto Chemical Co., St. Louis, Mo.
Morris and Co., Chicago. Ill.
Morris and Co., Oklahoma City, Okla.
Mulford and Co., H. K., Philadelphia, Pa.

National Ammonia Co., St. Louis, Mo.
National Aniline and Chemical Co., Inc., Buffalo, N. Y.
National Association of Refrigeration, Chicago, Ill.
National Biscuit Co., New York City, N. Y.
National Brick Manufacturers' Association, Indianapolis, Ind.
National Canners' Association, Washington, D. C.
National Carbon Co., Cleveland O.
National Carbon Co., Fremont, O.
National Cash Register Co., Dayton, O.
National Dairy Council, Chicago., Ill.
National Electric Lamp Association, Cleveland, O.
National Lamp Works of the General Electric Co., Cleveland, O.
National Lead Co., New York City.
National Lime Mfrs'. Association, Riverton, Va.
National Tube Co., Pittsburgh, Pa.
Nela Research Laboratory, Cleveland, O.
New Jersey Zinc Co., New York City.
Newlands Laboratories, Hartford, Conn.
Newport Chemical Works, Inc., Milwaukee, Wis.
Newport News Shipbuilding Co., Newport News, Va.
New York Shipbuilding Co., Camden, N. J.
Niagara Electrochemical Co., Niagara Falls, N. Y.
Nichols Laboratory, Knoxville, Tenn.
Nitro Products Co., Saginaw, Mich.
Nitrogen Products Co., Providence, R. I.
Norton Co., The, Worcester, Mass.
Nowak Chemical Laboratories, St. Louis, Mo.

Pabst Brewing Co., Milwaukee, Wis.
Packard Motor Car Co., Detroit, Mich.
Page Laboratory, Carl M., Chicago, Ill.
Paint Mfrs'. Association of the United States, Philadelphia, Pa.
Palmer Tire and Rubber Co., St. Joseph, Mich.
Parke Davis and Co., Detroit, Mich.
Patent Vulcanite Roof Co., Albany, N. Y.
Patent Vulcanite Roofing Co., Chicago, Ill.
Pennsylvania Railroad, Altoona, Pa.
Pennsylvania Salt Mfg. Co., Philadelphia, Pa.

Pfanstiehl Co., Inc., North Chicago, Ill.
Pfaudler Mfg. Co., Rochester, N. Y.
Pfister and Vogel Leather Co., Milwaukee, Wis.
Pierce-Arrow Auto Co., Buffalo, N. Y.
Pittsburgh Plate Glass Co., Pittsburgh, Pa.
Pittsburgh Testing Laboratory, Pittsburgh, Pa.
Portland Cement Association, Chicago, Ill.
Powers-Weightman-Rosengarten Co., Philadelphia, Pa.
Pratt and Whitney Mfg. Co., Hartford, Conn.
Precision Instrument Co., Detroit, Mich.
Proctor and Gamble Mfg. Co., Ivorydale, O.
Providence Gas Co., Providence, R. I.
Pyroelectric Instrument Co., Trenton, N. J.

Reed Laboratory, New York City, N. Y.
Remington-Arms Union Metallic Cartridge Co., Bridgeport, Conn.
Reo Motor Car Co., Lansing, Mich.
Research Corporation, New York City.
Research Laboratory of Chicago, Chicago, Ill.
Rich Steel Products Co., Battle Creek, Mich.
Rising Paper Co., D. B., Housatonic, Mass.
Rochester Button Co., Rochester, N. Y.
Roessler and Hasslacher Chemical Co., Perth Amboy, N. J.
Rubber Trade Laboratory, Newark, N. J.
Russia Cement Co., Gloucester, Mass.

Sangamo Electric Co., Springfield, Ill.
Schoenhofen Brewing Co., Chicago, Ill.
Schulze Baking Co., Chicago, Ill.
Scientific Materials Co., Pittsburgh, Pa.
Scovill Mfg. Co., Waterbury, Conn.
Sears-Roebuck Co., Chicago, Ill.
Sharpe and Doane, Baltimore, Md.
Shell Co., The, Martinez, Cal.
Simon and Co., R. H., Easton, Pa.
Sinclair Refining Co., East Chicago, Ill.
Smith and Dove Mfg. Co., Andover, Mass.
Solvay Process Co., Solvay, N. Y.
Souther Cottonseed Oil Co., Montclair, N. J.
Spears Sons, E. Alden, Cambridge, Mass.
Sperry Gyroscope Co., Brooklyn, N. Y.
Sprague, Warner and Co., Chicago, Ill.
Spreckels Sugar Co., San Francisco, Calif.
Squibb and Sons, C. R., New York City.
Standard Aero Corp., New York City
Standard Aeroplane Co. of New York, Plainfield, N. J.
Standard Oil Co., Bayonne, N. J.

Standard Oil Co., El'Segundo, Cal.
Standard Oil Co., Richmond, Cal.
Standard Oil Co., Whiting, Ind.
Stevens Mills, North Andover, Mass.
Stewart Warner Speedometer Corp., Chicago, Ill.
Stone and Webster, Engr. Corp., Boston, Mass.
Strathmore Paper Co., Mitteneague, Mass.
Structural Materials Research Laboratory, Chicago, Ill.
Studebaker Corp., Detroit, Mich.
Studebaker Corp., South Bend, Ind.
Sturtevant Aeroplane Co., Boston, Mass.
Sturtevant Co., B. F., Boston, Mass.
Swift and Co., Chicago, Ill.

Taylor Instrument Co., Rochester, N. Y.
Taylor Logan Co., Holyoke, Mass.
Textile Trade Laboratory, Newark, N. J.
Thomas, Arthur H., Philadelphia, Pa.
Titanium Alloys Mfg. Co., Niagara Falls, N. Y.
Toch Brothers, New York City.
Todd Co., G. W., Rochester, N. Y.
Tropical Paint and Oil Co., Cleveland, O.
Trostel and Sons, Albert, Milwaukee, Wis.

Underwriters' Laboratories, Chicago, Ill.
Union Iron Works, San Francisco, Cal.
Union Switch and Signal Co., Swissvale, Pa.
United Alloy Steel Corp., Canton, O.
United Gas Improvement Co., Philadelphia, Pa.
U. S. Conditioning and Testing Co., New York City.
U. S. Glue Co., Milwaukee, Wis.
U. S. Industrial Alcohol Co., New York City.
U. S. Rubber Co., Bristol, R. I.
U. S. Rubber Co., Malden, Mass.
U. S. Smelting Co., New York City.
U. S. Smelting, Refining and Mining Co. (Central Research Laboratory), Mass. Inst. of Technology, Cambridge, Mass.
U. S. Steel Corp., Homestead, Pa.
U. S. Steel Corp., New York City.
U. S. Tire Co., New York City.
Universal Oil Products Co., Chicago, Ill.

Van Schaack Brothers Chemical Works, Chicago, Ill.
Ventura Refining Co., Ventura, Cal.
Vesta Accumulator Co., Chicago, Ill.
Victor Chemical Works, Chicago, Ill.
Victor Talking Machine Co., Camden, N. J.
Virginia-Carolina Chemical Co., Richmond, Va.

Wahl and Henius Co., Chicago, Ill.
Warren and Co., S. D., Cumberland Mills, Me.
Washburn-Crosby Co., Minneapolis, Minn.
Welsbach Co., Gloucester, N. J.
Western Electric Co., Hawthorne Station, Chicago, Ill.
Western Electric Co., New York City.
Western Precipitation Co., Los Angeles, Cal.
Westinghouse Airbrake Co., Wilmerding, Pa.
Westinghouse, Church, Kerr and Co., New York City, N. Y.
Westinghouse Electric and Mfg. Co., East Pittsburgh, Pa.
Westinghouse Lamp Co., Bloomfield, N. J.
Weston, Bryon and Co., Dalton, Mass.
Weston and Sampson, Boston, Mass.
White Dental Co., S. S., Philadelphia, Pa.
Will Corporation, Rochester, N. Y.
Willys Overland Co., Cleveland, O.
Wilson and Co., Chicago, Ill.
Winchester Repeating Arms Co., New Haven, Conn.

Yocum, John H., Newark, N. J.
Youngstown Sheet and Tube Co., Youngstown, O.

COOPERATION OF THE PORTLAND CEMENT ASSOCIATION AND LEWIS INSTITUTE IN EXPERIMENTAL STUDIES OF CONCRETE.

By Duff A. Abrams.[1]

To the engineer of a generation ago, concrete was known as a substitute for stone masonry in the construction of massive works, such as foundations, bridge piers, abutments and arches, retaining walls, dams, breakwaters, fortifications, etc. Concrete offers a high resistance to compressive stresses but is somewhat deficient in tensile resistance. Reinforced concrete is a combination of concrete with steel in such a manner that the steel members take the tensile stresses and thus form a structural unit of a new type. In certain members, such as columns, the steel assists in taking the compressive stresses.

Reinforced concrete as an important structural material is a development of the past twenty years. From a small beginning reinforced concrete has come to be one of the most important materials of construction. At the present time it is widely used for buildings, roads, pressure pipes, ships, and almost an infinite variety of other purposes which touch every phase of modern life.

Exhaustive experimental studies of reinforced concrete have been carried out by many investigators in the United States and Europe. These researches have developed a large fund of information, so that well-informed engineers are now able to design and build reinforced-concrete structures with the same confidence that has characterized the use of other structural materials.

Concrete is a combination in suitable proportions of three entirely different materials: cement, water and aggregate. It is notable that our knowledge of the properties of concrete and concrete materials has not kept pace with the developments in the field of reinforced-concrete construction. It may seem somewhat anomalous to say that at the present time we know a great deal more of the properties of reinforced concrete than of concrete. If we make certain assumptions as to the properties of the concrete to be used, we can design reinforced members and structures which will perform their proper functions. However, it is impossible for the engineer to estimate in advance with any degree of certainty the strength and other properties of the concrete made from definite proportions of given materials which are mixed and placed in a given manner. This condition has resulted from a lack of a complete analysis of the principles of concrete mixtures and has led to rule-of-thumb methods of selecting materials and proportioning.

---

[1] Professor in Charge, Structural Materials Research Laboratory, Lewis Institute, Chicago.

The problems which generally confront the engineer in designing and estimating the cost of concrete structures are as follows:

1. What quality of concrete is most economical?
2. Are the aggregates near at hand suitable?
3. Of several aggregates, all of good grade, which is the best for the purpose?
4. What tests shall be made to determine the suitability of aggregates?
5. How shall the materials be proportioned, mixed and placed in order that concrete of the highest quality may be produced at lowest cost?
6. What is the effect of certain changes in the proportions of the materials?
7. What is the effect of exposures or service conditions on the permanency of the concrete?

The aggregate constitutes 75 to 90 per cent of the weight of the material in concrete; this makes it important that aggregates which are found near at hand be used if they can be shown to be suitable.

Our present knowledge as to the fundamental properties of concrete and the exact manner in which the character and the proportions of the constituent materials influence the strength and other properties is by no means complete. When we consider the almost endless variety of materials available for concrete aggregate and the numberless combinations which may be made in the size of aggregate and the relative proportions of cement, water and aggregate, it is not surprising that many divergent opinions are now current as to the influence of these factors.

Lack of definite information on many of the questions raised above has led to a demand for a more comprehensive study of the properties of concrete and concrete materials. In an effort to supply this information, the Structural Materials Research Laboratory was organized in 1914. This Laboratory is located at Lewis Institute, an educational institution in Chicago. The work of the Laboratory is carried out through the cooperation of the Institute and the Portland Cement Association. The Portland Cement Association includes practically all of the manufacturers of Portland cement in the United States, Canada and Cuba. The work of this Laboratory is an example of the cooperation, not only of the manufacturers in an effort to solve the problems arising in the use of their product, but also a striking example of the successful cooperation of an engineering college with a manufacturing industry of international scope.

The control of the policies of the Laboratory is vested in an advisory committee consisting of representatives of Lewis Institute and the Portland Cement Association. The Association is represented through its Committee on Technical Problems, of which F. W. Kelley, Albany, N. Y., is chairman.

The Laboratory is supplied with all necessary equipment for both physical and chemical experiments. There is now a permanent staff of 23 employes engaged in this experimental work. Tests are now being made at the rate of about 50,000 per year.

Experiments already carried out have shown that the most elemental principles of concrete mixtures have escaped notice in the practical use of the material and in the tests heretofore reported. Exhaustive studies of the properties of concrete made of the same materials mixed in widely different proportions have brought out many new facts. It has been shown that the size and grading of the aggregate and the quantity of cement used affect the strength of the concrete solely due to their influence on the relative quantity of water required to produce a plastic mix. Other factors being equal a coarse, well-graded aggregate gives better results in concrete than a fine aggregate, solely due to the fact that a plastic mix can be produced with a smaller quantity of water when the coarse, well-graded aggregate is used. Increasing the quantity of cement in the mix produces no beneficial result unless we at the same time reduce the relative quantity of mixing water used. This conclusion should be contrasted with the feeling of security which is reflected in all text-books, specifications and building codes, due to the use of richer mixes of concrete, with no reference whatever to the water factor. These experiments and others carried out on closely related lines have furnished the foundation for a correct theory of concrete mixtures and for a rational method of proportioning the constituent materials. A brief discussion of one phase of these investigations was published in an article by the writer in the May 2, 1918, issue of the *Engineering-News Record*. (The same article was published in the *Concrete Highway Magazine*, May, 1918; and in the *Canadian Engineer*, June 6, 1918.)

A study of the effect of organic impurities in natural sands has led to a colorimetric test made by digesting the sand in a dilute solution of sodium hydroxide. This test has proven of great value in the preliminary examination of sand samples. The use of this test will no doubt have an important influence in preventing inferior or defective concrete work due to the presence of organic loam and similar materials in concrete sands. This study of organic impurities in sands was inaugurated through the cooperation of Committee C-9 on Concrete and Concrete Aggregates of the American Society for Testing Materials, of which S. E. Thompson, Boston, Mass., is chairman. The first year's study was financed by Committee C-9. For a brief description of the test see Circular No. 1, Structural Materials Research Laboratory, "Colorimetric Test for Organic Impurities in Sands."[1]

Many other phases of concrete work have been the subject of experimental research. The following may be mentioned as among the more comprehensive studies:

Influence of various factors on the resistance of concrete to impact and abrasive stresses;

Standardization of tests of cement, aggregates, concrete and concrete products;

---

[1] See also *Proceedings*, Am. Soc. Test. Mats., Vol. XVII, Part I, p. 327 (1917).

Study of the relative merits of different materials for concrete aggregate;

Study of the interrelation of strength, density, modulus of elasticity and other properties;

Study of the physical and chemical properties of cement;

Effect of fineness of cement on the properties of concrete;

Effect of various admixtures in concrete;

Study of concrete in alkali soils and waters;

Influence of rolling, tamping, vibrating and other methods of manipulation on the properties of concrete;

Storage of commercial liquids in concrete;

Field tests of concrete and concrete aggregates;

Study of the performance of concrete mixers;

Development of a suitable concrete of light weight for use in ships and other floating structures;

Effect of age and curing conditions on the properties of concrete.

New uses of concrete give rise almost daily to demands for information which is not now available. It is one of the functions of this Laboratory to supply this demand as to the best method for adapting concrete to untried construction. The use of concrete in the construction of ocean-going ships is one of the most striking developments of the world war. Ship construction demands concrete of high strength and light weight. Such information as we have collected on this subject has been placed in the hands of the U. S. Shipping Board.

It is the policy of the Laboratory to cooperate with technical societies and other testing laboratories to the fullest extent. Experimental work has already been carried out in cooperation with the following committees of the American Society for Testing Materials: C-1 on Cement; C-6 on Drain Tile; C-9 on Concrete and Concrete Aggregates, and with the Committee on Concrete Products of the American Concrete Institute. The results of this research work will become available for the information of all concerned as soon as the experimental work along a given line is sufficiently complete that definite conclusions are available.

While these experimental studies are being carried out through the cooperation of the cement manufacturers, it should be noted that none of this work has been directed toward the solution of strictly manufacturing problems or with a view to economics in the operation of cement mills. The aim has been to render every assistance in the development of improvements in the quality of concrete, and to adapting concrete to meet the demand for structural material in new fields. This broad-minded policy on the part of the manufacturers is a reflection of the most advanced ideas of business ethics which finds expression in the theory that the obligation of the manufacturer does not end in the production and sale of a first-class product, but extends as well to rendering every service in his power to assist his client to a proper use of the product to the end that it may serve its purpose in the most economical manner.

These researches will undoubtedly exert an important influence in rationalizing concrete and reinforced concrete construction, to the end that better and more permanent work will be secured at a lower cost. Such benefits as may be derived from these experiments will come to the general public.

SOME PRACTICAL VIEWS OF RESEARCH.

By J. S. Unger.[1]

Twenty years ago the term Industrial Research was not as common in the steel business as it is to-day. At that time Industrial Research was not usually carried on by some one especially designated to do this work, but by the individual or joint efforts of the chemist, the engineer or the department superintendent of a plant.

I am in hearty agreement with the thought brought out by Dr. Howe. It should be the aim to carry out such tests as will approximate the trying conditions of service. This point is often lost sight of in making an investigation. The following examples will illustrate what I mean: A proof load test for a chain is better than a chemical analysis of the material; a hydrostatic test for a pipe or tube rather than a microscopic examination; exposure of metallic sheets to atmospheric corrosion instead of their rate of solubility in dilute acid; a ballistic test of a helmet in place of a determination of the heating curve of the steel; the softening point of a brick under working conditions in place of the temperature at which a fragment becomes liquid; the performance of a railroad rail, wheel, or axle on an experimental track rather than a drop test. Many other cases could be given, but these should be sufficient to point out the necessity for what might be called a working test.

Dr. Little points out: "It is beginning to be recognized that there is no valid distinction between scientific research and industrial research." This is being recognized by our engineering schools, many of which are giving instruction in engineering subjects closely approaching standard practice, depending on how closely the instructors keep in contact with such practice and on their ability to incorporate the same in their instruction.

Practical research is extremely valuable, but it must be carefully planned beforehand to be of the greatest value. An investigation must have a definite aim. It should be possible of execution by works, methods or by such modification or changes as may afterwards be used in the regular process of manufacture.

---

[1] Manager, Central Research Laboratory, Carnegie Steel Co.

It is foolish to investigate a subject by methods which can not be commercially applied on account of their excessive cost, their interference with the preceding or subsequent operations and the uncertainty of their value when applied. For instance, the addition of ferro-manganese in large lumps to the ladle will show a lower manganese loss, but can not be recommended owing to the uncertainty of its thorough melting and distribution.

A general survey must be made of the entire situation. An experiment may be of value to a single department, but may prove to be an inconvenience and even an injury to a dependent department.

It may also happen that objections may be raised to an experiment through apprehension that something may be developed which might be considered a criticism of works methods. At other times workmen may, through personal reasons, do great damage to the practical and successful use of a method or process by their stupid prejudice, or opposition.

An investigation may show negative results, leading the management to condemn or stop further experiments along this or other lines. Negative results are valuable in showing what should not, or can not, be done. Failures are of frequent occurrence, but this should not be discouraging, as a proportion of 10 per cent of successful, practical, useful experiments is high.

There is a tendency in the shops to take too much for granted, particularly if printed, by believing some theory, or accepting as a fact a statement made by some one else, without requiring proof. All shops have their pet beliefs, many of which are wrong and must be proved so before a new opinion will prevail.

In a paper given by Dr. Johnston, a few weeks ago, he pointed out that Research is an insurance against ignorance and costs very much less than what we ordinarily pay for fire or accident liability. I was further impressed by his statement that of a certain 2200 schemes submitted, only five were thought to be of sufficient value to merit a trial and of these five, none were successful.

Research must be properly carried out. Many meritorious suggestions or experiments fail because they have been tried but once. Conclusions are best when based on a large number of results, rather than a few. Sometimes important features of the trial are omitted or carelessly executed. I have in mind a case where a trial tool was jammed and broken in a machine by the ignorance of the operator, who reported to his foreman that the tool was "no good," and the experiment was stopped. As a result of the excellent performance of a similar tool at another plant, the tool was tried again about a year later and proved very successful.

A rather humorous example developed as the result of the trial of several kinds of soil fertilizers, consisting of barnyard manure, ground limestone, and a super-phosphate. Instead of using each fertilizer on separate plots, the experimenter must have believed that if each was good, when all were combined they would be better. All were put on the same plot, giving a pronounced increased yield, but it was impossible to determine the individual merit of any.

In research work, it is advisable to work with quantities approaching actual size as nearly as possible. To make a few ounces of metal in a crucible and afterwards forge this metal into a specimen ½ in. in diameter, then heat-treat and test the material to show particularly high qualities, is neither impressive nor convincing evidence to one who must prepare a similar metal in 50-ton lots, cast it into ingots weighing several tons, roll it in a mill into pieces of 12 in. in diameter and later test the rolled material. The same results cannot be obtained in the larger mass, yet the trade may demand the properties shown by the smaller piece.

Many tests are regularly made which do not represent service conditions and can only be classed as checking or uniformity tests. Does it not appear absurd to test a cement briquette or a steel column by a tension test? Such tests have little practical value other than a check on the uniformity of the material. Do we not need to change many of our methods of testing to conform more closely to service conditions?

The essentials to successful Research Work are: An adequate and complete equipment, so as to be able to duplicate works conditions—if such is not possible, the use of the facilities of the works; the cooperation of the works management, foremen and men in an investigation; the creation of an optimistic and enthusiastic sentiment in solving works problems; and the keeping of a careful record of the work done and the conclusions arrived at.

Research of greatest value to the steel industry is that careful study of things comparatively well known, to substitute facts for theories or beliefs, to promote desirable economies or improve qualities, and to distribute such information to those who may be able to use it in an intensely practical way.

COOPERATION BETWEEN GOVERNMENTAL BUREAUS AND THE INDUSTRIES IN RESEARCH ON WAR PROBLEMS.

By S. R. Church.[1]

Dr. Reese has shown in graphic manner the progress of research by one large manufacturing company and while the example cited is extraordinary, the whole trend of the discussion to-night indicates that the problems of production will be largely handled by research laboratories directly connected with the industrial companies or employed by them.

However, in the development of the military program there are obviously many research problems that must of necessity be worked out by the government in the laboratories of its various and numerous departments and bureaus. Many of these problems will, owing to the exigencies of the situation, be placed in the hands of investigators having imperfect knowledge of the materials to be dealt with. Naturally these investigators will turn to the producers of the materials for information as well as for samples. Needless to say the manufacturers are anxious to furnish information and advice freely and fully. My observations lead me to believe that too often the producer is not afforded opportunity to be of the greatest possible assistance in cooperative researches of this kind. For example, he often receives a circular letter from some government office, without any indication of the purpose for which the materials are to be used, and without complete description of the materials required. Sometimes these letters include requests for prices and quantities available and the manufacturer may often be unable to answer intelligently without knowledge of the technical purpose and relative urgency of the proposition. Sometimes, by further correspondence or personal interview, a satisfactory solution is reached. My purpose is to urge that producers be afforded better facilities to give full service in these matters, and to this end I suggest that, wherever circumstances permit, the responsible technical heads of well-recognized producing organizations be approached in person by well-accredited representatives of government departments, so that a mutual feeling of assurance may be had regarding the confidential character of the information exchanged.

---

[1] Manager, Tar and Oil Division, General Mfg. Dept., The Barrett Co., New York City.

GRAIN SIZE OF IRON AS AFFECTED BY TEMPERATURE.[1]

By D. J. McAdam, Jr.

SUMMARY.

This paper is a continuation of a paper published in the Proceedings of last year.[2] In the present paper, results are recorded of grain-size measurements made at the U. S. Naval Engineering Experiment Station on the specimens described in the previous paper and on additional specimens. Curves are published showing the effect of temperature on grain size. The paper discusses methods of recording and plotting results of grain-size measurements. The significance of the results of grain-size measurements is discussed and the results are compared with the few results previously published.

---

[1] This paper is published by permission of the Secretary of the Navy.

[2] D. J. McAdam, Jr., "Annealing Temperatures and Grain Growth," *Proceedings*, Am. Soc. Test. Mats., Vol. XVII, Part II, p. 58 (1917).

GRAIN SIZE OF IRON AS AFFECTED BY TEMPERATURE.[1]

BY D. J. McADAM, JR.

Many observations and experiments have been made by various investigators to determine the laws of grain growth of cold-worked iron and low-carbon steel. The effect of strain gradient, of temperature gradient and of various other factors on grain size, have been thoroughly discussed. In nearly all the recorded experiments, however, attention has not been confined to the effect of temperature alone. The influence of temperature has always been somewhat masked by the influence of other factors, such as strain gradient and temperature gradient.

The experiments recorded in the present paper were made at the U. S. Naval Engineering Experiment Station with the intention of determining the effect of temperature alone on equilibrium grain size of ingot iron. Other factors, such as strain gradient and temperature gradient, were therefore eliminated as much as possible.

The general method of investigation was outlined in a paper published in the Proceedings last year.[2] Ingot iron was compressed in a 300,000-lb. testing machine, the percentage reduction in thickness being taken as a measure of the degree of deformation. Specimens, after various degrees of deformation, were then annealed at various temperatures and the microstructures observed. In the previous paper, photomicrographs were included and the results were summarized as well as possible without grain-size measurements. The principal conclusions were as follows:

1. For cold wrought ingot iron that is as free as possible from deformation and temperature gradients, there is a range of temperature, extending from about 900 to 1450° F., in which there is little or no coalescence of the completely recrystallized grains. The lower limit of the range of complete recrystallization varies, of course, with the amount of previous deformation.

---

[1] This paper is published by permission of the Secretary of the Navy.

[2] D. J. McAdam, Jr., "Annealing Temperatures and Grain Growth," *Proceedings*, Am. Soc. Test. Mats., Vol. XVII, Part II, p. 58 (1917).

2. For cold wrought ingot iron there is a coalescence range extending from about 1450° F. to the lower limit of the gamma range. Within this range the grain size increases rapidly with increase in temperature.

Since the publication of the former paper, grain-size measurements have been made on the specimens there described. Many additional experiments have also been made and the grain sizes of the various specimens have been measured. The grain-size measurements have been confined to completely recrystallized material.

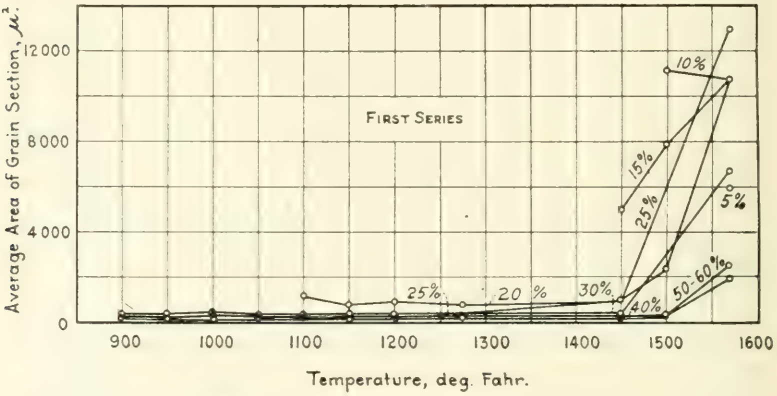


Fig. 1.—First Series. See Table II.

The method used in grain-size measurements, which is due to Jeffries,[1] is as follows:

A magnified image of the metal is focused on a sheet of thin paper on which a circle about 10 cm. in diameter is drawn. The number of grains, both those entirely included in the circle and those cut by the circumference, are then counted. The number of marginal grains multiplied by a factor, approximately 0.6, is added to the number of entirely included grains. From this number, the area of the circle, and the magnification, the number of grains per unit area is calculated.

---

[1] Z. Jeffries, "Determination of Grain Size in Metals," *Bulletin*, Am. Inst. Min. Engrs., December, 1915.

TABLE I.—FIRST SERIES: NUMBER OF GRAINS PER SQUARE MILLIMETER.

Temperature, deg. Fahr.	Time, hr.	Previous Reduction in Thickness, per cent.								
		5	10	15	20	25	30	40	50	60
900	8.5	....	....	....	....	....	3100	3472	4800	5180
950	16.0	....	....	....	....	....	2780	4170	4890	6920
1000	8.5	....	....	....	....	....	2390	4140	5990	6520
1050	2.0	....	....	....	....	2500	2860	3930	6220	7220
1100	9.0	....	....	....	939	2810	2890	4060	5470	6930
1150	2.0	....	....	....	1360	2860	3030	4160	6860	7570
1200	8.0	....	....	....	1180	2650	2770	4750	6530	7650
1275	4.0	....	....	....	1400	2840	2970	3670	6530	7790
1450	2.75	....	....	203	1060	1060	2900	4310	7000	9560
1500	1.5	....	90	127	419	....	....	3270	3770	4620
1570	2.5	167	93	93	93	77	151	517	409	404

TABLE II.—FIRST SERIES: AVERAGE AREA OF GRAIN SECTION IN μ^2.

Temperature, deg. Fahr.	Time, hr.	Previous Reduction in Thickness, per cent.								
		5	10	15	20	25	30	40	50	60
900	8.5	....	....	....	....	....	322	288	208	193
950	16.0	....	....	....	....	....	359	240	204	144
1000	8.5	....	....	....	....	....	418	241	167	153
1050	2.0	....	....	....	....	400	349	254	161	138
1100	9.0	....	....	....	1 060	356	346	246	183	144
1150	2.0	....	....	....	735	350	330	240	146	132
1200	8.0	....	....	....	847	377	360	210	153	131
1275	4.0	....	....	....	714	352	337	272	153	128
1450	2.75	....	....	4 926	943	943	345	232	143	105
1500	1.5	....	11 110	7 874	2 386	....	....	306	265	216
1570	2.5	5 990	10 750	10 750	10 750	12 990	6 622	1 934	2 444	2 475

First Series.

This series of experiments was described in the previous paper. Grain-size measurements, however, had not been made at that time. The results of grain-size measurements are, therefore, included in the present paper in Table I. From these results, the average areas of grain section in μ^2 are calculated. The results are recorded in Table II and are shown in diagrammatic form in Fig. 1.

Table III.—Second Series, Annealed 7 Hours: Number of Grains per Square Millimeter.

Temperature, deg. Fahr.	Reduction of Thickness, per cent.				
	30	40	50	60	75
1000	4510	5150	6460	8030	....
1100	3440	4820	5690	8160	....
1200	3430	2830	6410	6850	....
1300	5960	4380	5750	7720	....
1400	4340	3910	6860	6140	....
1450	3980	3590	5100	6240	....
1475	1635	2520	3160	4540	4030
1495	556	1860	2270	2210	3010
1525	1070	900	2070	1290	2110
1575	45	71	69	69	120
1590	....	110	....	120	....

In the discussion of the previous paper, there was criticism of the fact that the times of annealing were not the same for the various temperatures. Though the author felt that the conclusions were not vitiated by this fact, care was taken in the following described experiments that the time of maintenance at each temperature was approximately constant for each series.

TABLE IV.—SECOND SERIES, ANNEALED 7 HOURS: AVERAGE AREA OF GRAIN SECTION IN μ^2.

Temperature, deg. Fahr.	Reduction of Thickness, per cent.				
	30	40	50	60	75
1000	222	194	155	124	....
1100	291	207	176	122	....
1200	292	353	156	146	....
1300	168	228	174	129	....
1400	230	256	146	163	....
1450	251	278	196	160	....
1475	611	397	316	220	248
1495	1 798	538	440	452	332
1525	936	1 110	483	775	475
1575	22 900	14 080	14 490	14 490	8333
1590	....	9 090	8 333	....	...

TABLE V.—SECOND SERIES, ANNEALED 14 HOURS: NUMBER OF GRAINS PER SQUARE MILLIMETER.

Temperature, deg. Fahr.	Reduction of Thickness, per cent.				
	30	40	50	60	75
1000	6500	4440	6220	7910	....
1100	3040	3580	5410	5650	....
1200	1430	4980	7120	5080	....
1300	5410	4030	5410	6960	....
1400	4020	3670	3130	6040	....
1450	1845	2020	3270	4110	....
1475	1155	1950	2380	2320	3350
1495	534	1850	2560	1230	2250
1525	....	252	421	121	....
1575	45	109	69	60	120

TABLE VI.—SECOND SERIES, ANNEALED 14 HOURS: AVERAGE AREA OF GRAIN SECTION IN μ^2.

Temperature, deg. Fahr.	Reduction in Thickness, per cent.				
	30	40	50	60	75
1000	153	225	161	126	....
1100	329	279	185	177	....
1200	699	201	140	197	....
1300	185	248	185	144	....
1400	248	272	319	166	....
1450	541	495	306	243	....
1475	865	513	420	431	298
1495	1 872	540	397	813	444
1525	993	3970	2 375	8 260	473
1575	22 200	9170	14 490	16 680	8330

TABLE VII.—SECOND SERIES, ANNEALED 14 HOURS: AVERAGE DIAMETER OF GRAIN SECTION (NOMINAL) IN μ.

Temperature, deg. Fahr.	Reduction of Thickness, per cent.				
	30	40	50	60	75
1000	12.4	15.0	12.7	11.2	....
1100	18.1	16.7	13.6	13.3	....
1200	26.4	14.2	11.8	14.0	....
1300	13.6	15.8	13.6	12.0	....
1400	15.8	16.5	17.9	12.9	....
1450	23.3	22.3	17.5	15.6	....
1475	29.4	22.7	20.5	20.8	17.3
1495	43.3	23.2	19.8	28.5	21.1
1525	31.5	63.1	48.8	91.0	....
1575	149.0	95.7	120.5	129.0	91.5

SECOND SERIES.

Plates 1 in. thick were reduced by compression to a thickness of $\frac{1}{4}$ in. The plates $\frac{1}{4}$ in. thick were next annealed at 1300° F. for 2 hours. This material was then reduced by compression to varying thicknesses and annealed at the temperatures recorded in Tables III and V. Annealing experiments described in Tables III and V were for one and two periods, respectively, of about 7 hours each. Specimens were placed in the furnace after it had been raised to the proper temperature and were quenched in water at the end of the annealing period. The number of grains per square millimeter was calculated from the average of at least three measurements on each specimen.

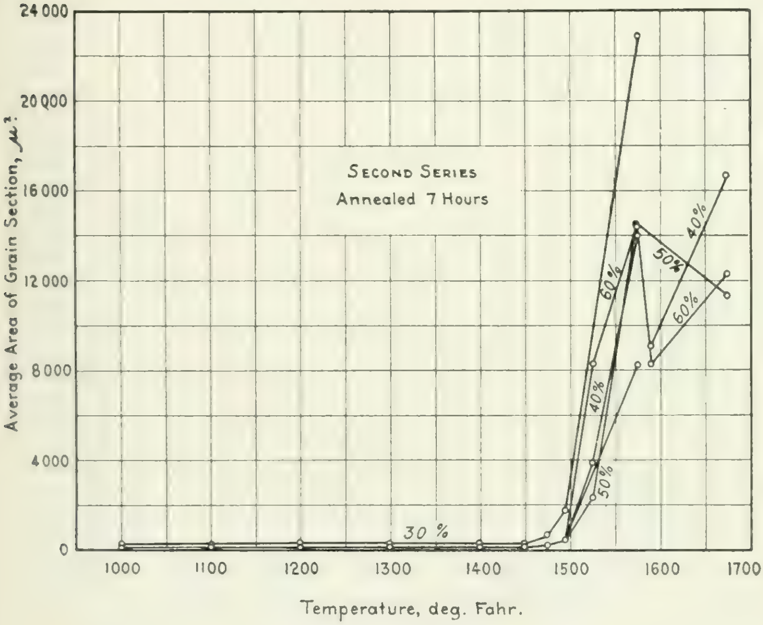


FIG. 2.—Second Series, Annealed 7 Hours. See Table IV.

From the results given in Tables III and V, the average areas of grain section in μ^2, and the average diameters (nominal) of grain section in μ, are calculated. The results are recorded in Tables IV, VI and VII, and are also plotted in Figs. 2, 3 and 4.

Third Series.

Experiments of the third series were made with the idea of determining, if possible, the influence on the temperature-grain size curve of still greater degrees of cold deformation. For this reason the preliminary reduction in thickness from 1 in. to $\frac{1}{4}$ in., followed by annealing, was omitted in this series. Plates 1 in. thick were given a preliminary annealing at 1525° F. for $1\frac{1}{2}$ hours; they were then reduced in thickness by the percentages recorded in Table VIII, and annealed for 7 hours at the temperatures recorded in Table VIII. After determination of the number of grains per square millimeter by the above described method, the average areas of grain section were calculated and recorded in Table IX, and have been plotted in Fig. 5.

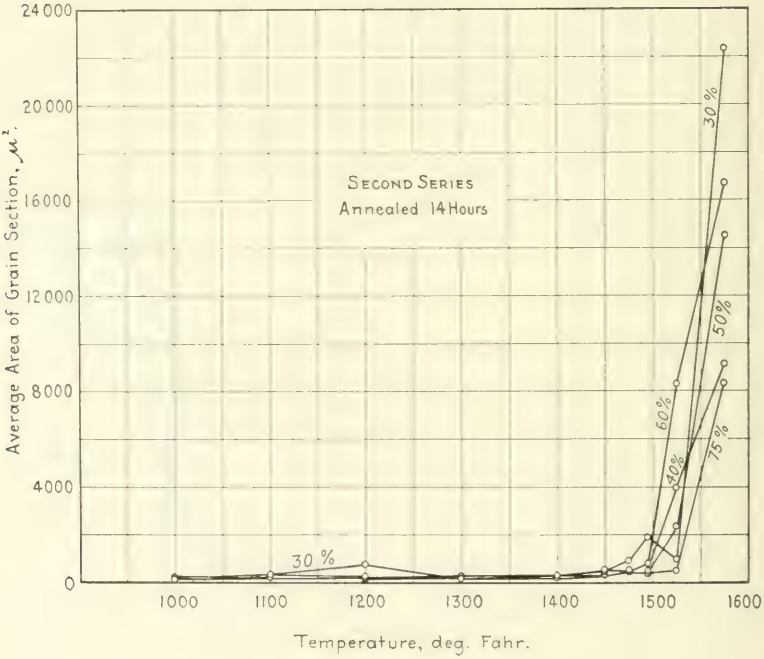


Fig. 3.—Second Series, Annealed 14 Hours. See Table VI.

Method of Expressing Grain Size.

The writer believes that the expression of results of grain-size measurements merely as numbers of grains per unit area is unsatisfactory. Values expressed in such a way can not be plotted so as to make clear the effect of temperature on either absolute or relative grain size. In a curve in which temperature is plotted against the number of grains per unit area, slight relative or absolute variations in the size of small

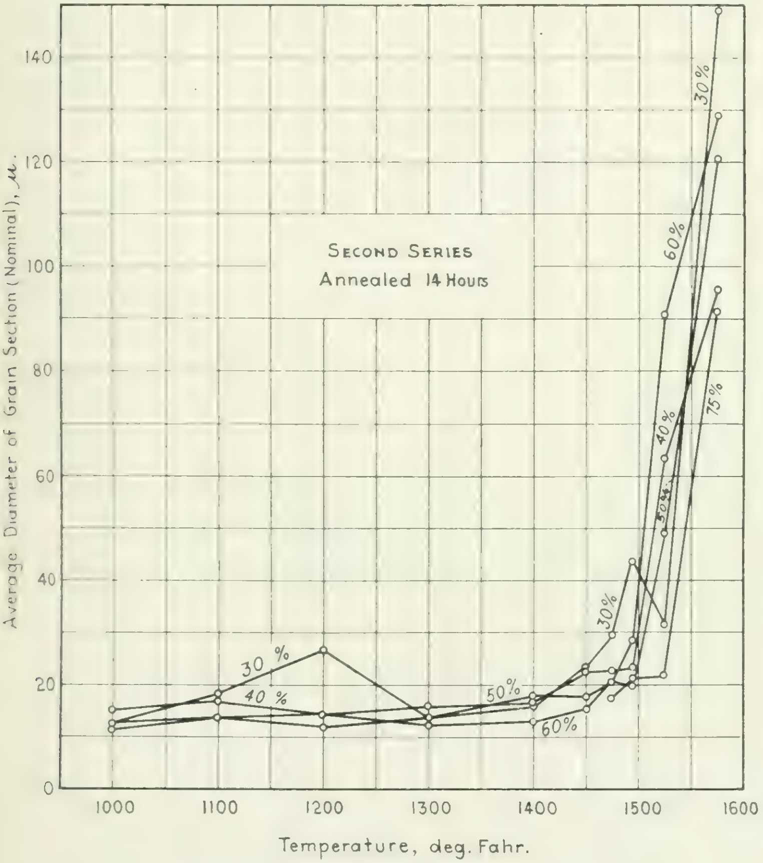


Fig. 4.—Second Series, Annealed 14 Hours. See Table VII.

TABLE VIII.—THIRD SERIES, ANNEALED 7 HOURS: NUMBER OF GRAINS PER SQUARE MILLIMETER.

Temperature, deg. Fahr.	Reduction of Thickness, per cent.							
	30	40	50	60	75	87	91	93
1000........	423	1070	4260	4130	6690	8380	7140	10 800
1150........	446	2010	3360	4230	5030	7301	9460	8 460
1250........	476	1250	1950	2430	3450	3710	4650	5 530
1350........	418	1350	1640	2820	3580	7930	4880	6 350
1400........	386	1350	1360	1770	3290	3610	3570	3 730
1450........	388	633	1080	1570	3100	2340	5690	3 580
1500.......	324	564	777	3670	572	1140	1150	1 350
1550........	336	232	407	541	495	639	735	533
1600........	70	83	149	403	77	59	85	57
1625........	...	....	....	147	196	196	205	258
1675........	...	....	....	....	....	....	191	150

TABLE IX.—THIRD SERIES, ANNEALED 7 HOURS: AVERAGE AREA OF GRAIN SECTION IN $\mu.^2$

Temperature, deg. Fahr.	Reduction of Thickness, per cent.							
	30	40	50	60	75	87	91	93
1000..........	2 360	598	234	242	149	119	140	92
1150..........	2 240	497	300	236	198	136	106	118
1250..........	2 100	800	512	411	290	269	215	180
1350..........	2 390	740	610	355	279	126	205	157
1400..........	2 590	740	735	564	303	277	280	268
1450..........	2 570	1 580	925	636	322	427	176	279
1500.........	3 080	1 770	1280	272	1 750	877	869	740
1550.........	2 970	4 310	2460	1840	2 020	1 560	1 360	1 870
1600...... ...	14 280	12 040	6710	{3703 {2480	4 761} 12 980}	16 940	11 760	17 540
1625..........	......	......	....	6802	5 100	5 100	4 878	3 875
1675..........	......	......	....	....	......	......	5 235	6 667

grains are magnified, while great relative or absolute variations in the size of large grains are minimized. From the results of the above-described experiments, therefore, nominal areas and diameters of grain sections have been calculated. Such values have the advantage of being at least proportional to actual grain dimensions. When these values are plotted, then, the form of the curve at once makes apparent the temperature - grain size relations.

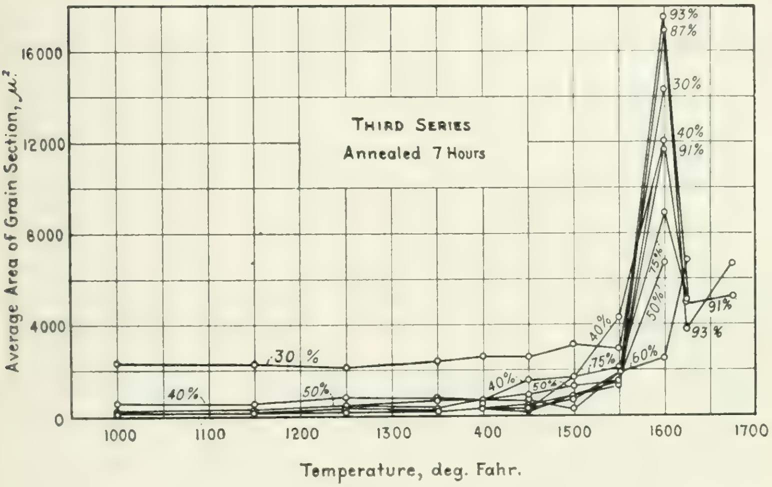


FIG. 5.—Third Series, Annealed 7 Hours. See Table IX.

CONCLUSIONS IN REGARD TO IRON.

Of the three series of experiments above described, it is believed that the second series gives the best demonstration of the effect of temperature on grain size. This series is really a double one, consisting of annealing experiments of 7 and 14 hours duration, respectively. The time variable was thus eliminated as much as possible. In this series also the grain size of the material was rendered as small and uniform as possible by a preliminary 75-per-cent reduction of thickness, followed by annealing. In this respect the material of the second series was in decided contrast to the material of the third series, in which the preliminary reduction of 75 per cent was omitted. In the material of the third series the original grain size, though generally large, was non-uniform. It might be expected, therefore, that this would produce irregularity in the results.

In all the above-described experiments, however, some irregularity of results might be expected on account of the impossibility of entirely eliminating strain gradient and temperature gradient. It is believed, nevertheless, that the results are sufficiently regular that definite conclusions can be drawn as to the effect of temperature on grain size of iron. It is believed, moreover, that the experiments justify the conclusions expressed in the previous paper and summarized in the third paragraph of the present paper. It seems to be established that below about 1450° F. the coalescence tendency of recrystallized grains is slight. Above about 1450° F. the coalescence tendency grows with increasing rapidity until it appears to reach its maximum about 1600° F.

The coalescence tendency in the case of iron, therefore, seems to be parallel to the magnetic change that takes place in iron at the same temperature. It is possible, of course, that this may be only a coincidence. It seems also possible that the change in properties of iron, resulting in a somewhat abrupt change of the temperature-magnetism curve, may have some effect on the temperature - grain size curve and cause the curvature to be more abrupt than it would otherwise be.

The temperature-grain size curves of iron published in the present paper, therefore, differ from the few which have been published up to the present time. Chappell[1] published some curves in which grain areas in μ^2 were plotted against temperatures in degrees Centigrade. As might be expected, since the measurements were made on specimens strained non-uniformly, the curves are not similar to those of the present paper. Howe, in a discussion of a paper by Stead and Carpenter,[2] publishes a curve which expresses approximately his ideas of the probable form of the temperature - grain size curve. In this curve, gradual grain growth from 450 to 850° C. (840 to 1560° F.) is assumed. Doctor Howe's curve and the discussion of the author's paper of last year emphasize the need of experiments to determine the effect of temperature on grain size of iron and other metals.

---

[1] Chappell, *Journal*, Iron and Steel Inst., 1914, No. 1, Figs. 20 and 21.

[2] Stead and Carpenter, "Crystallizing Properties of Electro-deposited Iron," *Journal*, Iron and Steel Inst., 1913, No. 2.

DISCUSSION.

Mr. Jeffries. MR. ZAY JEFFRIES (*by letter*).—When a cold-worked metal is heated above its recrystallization temperature, grain growth proceeds at a rapid rate for a short time and then more slowly. The higher the temperature the shorter the period of rapid growth. Some metals show a rapid increase in grain size at high temperatures for a period of only thirty seconds, after which the increase in grain size is extremely slow, in fact so slow as to be recognized with difficulty in a period of ten hours. I attempt to show this general condition in Fig. 1.

While this condition has been observed in the case of brass by Mathewson and Phillips, and in tungsten by the writer, an experiment on Armco iron indicates that the grain size increases with increase in time at a continuous rate. One set of results is as follows:

Armco iron which had been previously deformed about 25 per cent was heated to 850° C. (1562° F.) with the following results:

Time, hr.	Temperature, deg. Fahr.	Number of Grains per square Mm.
1	1562	318
10	1562	70
168	1562	2.5

Mr. McAdam's results at about the same temperature check the first two figures in a rough way. For example, his results taken from tables are as follows:

Time, hr.	Temperature, deg. Fahr.	Number of Grains per square Mm.
2½	1570	223[a]
7	1575	75[b]
14	1575	80[c]

---

[a] Average of nine determinations with varying reduction in thickness taken from Table I of his paper.

[b] Average of five figures given in Table III.

[c] Average of five figures given in Table V.

Mr. Jeffries.

Strictly speaking, there is no equilibrium grain size until all of a given piece of metal consists of a single grain. This is a theoretical condition which is seldom met in the use of metals. A condition is met frequently, however, which might be called an approximate equilibrium grain size. This would be interpreted as the grain size at a given temperature which would not increase to any marked extent with a considerable increase in time. In commercial annealings, for example, a difference in time of heating of a few hours would make but slight difference in the grain size after the approximate equilibrium grain size had been attained. It has always been assumed, however, that, excepting extreme cases of germination, an approximate equilibrium grain size for one temperature would not interfere with fairly rapid coalescence at a higher temperature. Mr. McAdam's results would indicate that an increase in temperature has but slight effect on grain growth in iron below 1450° F. Two reasons are suggested to account for the variations noted by Mr. McAdam from what might be called the normal condition. The normal grain size temperature curve as noted by Mathewson,[1] Tammann,[2] and the writer,[3] starts at the lower

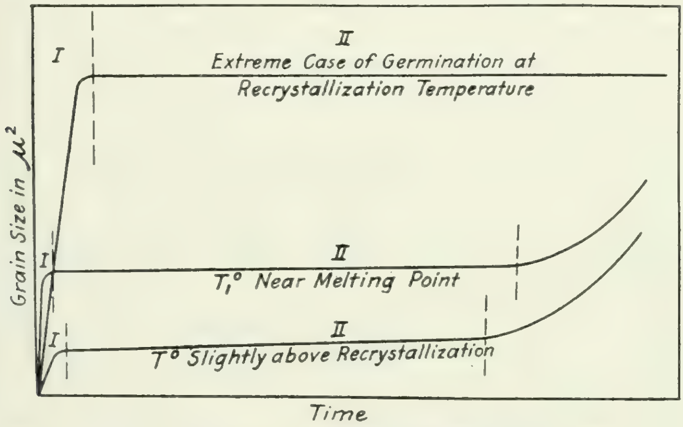


FIG. 1.—Curves Showing the Relation between Grain-Growth and Time for Three Typical Temperatures.

---

[1] *Am. Jour. Science*, Vol. XI, 1915, p. 549.

[2] *Lehrbuch der Metallographie*, 1914, p. 79.

[3] *Bulletin*, Am. Inst. Min. Engr., June, 1918, p. 1050.

Mr. Jeffries. left-hand corner of the diagram as used by Mr. McAdam and rises towards the upper right-hand corner. It is understood that the grain size does not change until a temperature is reached equal to or above that of crystallization. Above this temperature, however, the grain size should increase with increase in temperature. That Mr. McAdam did not note a decided increase in grain size with increase in temperature above 1000° F. may be due to:

1. The existence of strain gradients;
2. The rate of heating through the recrystallization range.

Two types of strain gradients should be present, namely, general and local. The general strain gradients would probably have been slight in the more severely deformed samples, but the local strain gradients can never be eliminated. These give rise to germination and consequently all grain growth at the time of recrystallization is germinative. This is shown in Fig. 1 and is indicated as Region I. When all of the strains have been removed then the force of growth depends upon grain size contrast. Growth will naturally be slower due to this force than to the forces of germination which are conducive to rapid coalescence. This is suggested as the reason for the sharp change in direction of the grain size-temperature curve given in Fig. 1, and designated Region II. As the grain size contrast increases a condition will obtain after a number of hours which permits growth at an increasing rate. In Region II the number of grains per unit area changes slowly with elapse of time, but the larger grains are increasing in size at the expense of the smaller and growth manifests itself in greater grain size contrast rather than fewer grains. Eventually the number of grains per unit area will decrease as the smaller grains become completely absorbed. All grain size-temperature curves, therefore, represent a comparison of Region II, that is, of the approximate equilibrium grain size.

Conditions may be brought about during germination which will make the grain size stable until a temperature several hundred degrees above the germinative temperature is reached. It is possible that Mr. McAdam's results are affected in this manner. The samples heated at the higher temperatures were

Mr. Jeffries. carried through their recrystallization temperatures at a comparatively rapid rate and hence a relatively fine grain structure would be expected. The samples heated at the lower temperatures would be held in their germinative temperature range a comparatively long time and hence would have a tendency to become coarse grained. In this manner there might be a general tendency for the grains produced at the lower temperatures to be relatively large as compared to the approximate equilibrium grain size for that temperature, and for those produced at the higher temperatures to be relatively small. Fig. 1 shows how the grain size at the recrystallization temperature can be carried far above that at higher temperatures in a given time. This may account for the flatness of Mr. McAdam's grain size-temperature curves below 1450° F.

Regarding the expression of the grain size in terms of the area in μ^2, I am convinced that it has merits for graphical representation over the method of reporting the number of grains in a given area. In the ordinary diagram the curve goes up as the grain size increases. This is always a desirable thing in connection with curves.

With reference to Mr. McAdam's observation that the grain size of ingot iron is less at 1650 than at 1600° F., it is interesting to note that Brooke and Hunting[1] have reported that in this material a constituent insoluble in non-gamma iron separates immediately below A_3. This would introduce mechanical obstruction to grain coalescence and would tend to make small grains stable.

Mr. McAdam. MR. D. J. MCADAM, JR. (*Author's closure by letter*).—Mr. Jeffries, in his discussion of my paper, comments on the fact that the temperature-grain size curves there shown differ in form from what he calls the "normal" curve. He gives three references as authority for the statement that the "normal" curve starts in the lower left-hand corner of the diagram and rises toward the upper right-hand corner. Having thus summarily settled the question of the normality of the curves, he claims that the alleged abnormality is due to two causes acting in combination: (1) local strain gradients, and (2) rapid heating through the recrystallization range.

---

[1] *Journal*, Iron and Steel Inst., No. 2, 1917, pp. 233–250.

Mr. McAdam. If I understand Mr. Jeffries' reasoning correctly, his theory is that the grain sizes of my specimens depend primarily on what he calls "germinative" growth taking place in the recrystallization period; he considers that the growth taking place after recrystallization is of secondary importance. In conversation with the writer, Mr. Jeffries stated that the correct way to make a temperature-grain size curve would be to use the same specimen for determining the entire curve, heating for the required time, first at the lowest temperature, then at the next higher temperature, etc.

Although the writer's experiments had led him to believe that Mr. Jeffries is mistaken, some additional experiments have since been made to test the theories expressed in Mr. Jeffries' discussion. Since sufficient time is not available to incorporate the new results in the present discussion, the writer can only say that the additional experiments have confirmed the results given in the original paper, and indicate that Mr. Jeffries is mistaken in his criticism. The additional experiments will be published in a later paper.

CHANGES WITHIN THE CRITICAL RANGE OF A GIVEN STEEL: FROM Ac_1 TO Ac_{3-2}.

By J. G. Ayers, Jr.

SUMMARY.

The object of this paper is to describe briefly the most important metallographic changes occurring in the critical range of steels in order that a clear mental picture may be formed of the resulting microstructures, and further discussion and investigation of this important transformation stimulated.

The procedure followed was to heat one end of a piece of 0.50-per-cent carbon steel well above its range and quench the entire piece in water. This resulted in the formation of practically every structure which occurs in quenching such steel in water from various temperatures within and above its range.

After polishing and etching, sixteen photomicrographs were taken continuously across the specimen, thus depicting every change resulting in the microstructure. Photomicrographs of higher magnification were taken to show in more detail the structural changes occurring at representative points in the transformation. The structure shown in each case is briefly described.

CHANGES WITHIN THE CRITICAL RANGE OF A GIVEN STEEL: FROM Ac_1 TO Ac_{3-2}.

BY J. G. AYERS, JR.

There is perhaps no phenomenon of which we make further use for our scientific and commercial progress than that which we commonly call the critical changes or transformations in steel heated through the proper temperature range. Our mastery over distance by air, land or sea has been more or less dependent upon the extent to which we have been able to make use of this common phenomenon. While we have endeavored to choose materials which respond more and more advantageously to our wants after undergoing these transformations, can we say with surety that we are getting a 100 per cent response from a given material in actual practice? Has not possibly the success which has followed the discovery or application of a new analysis led us to drop the old before we really knew or fully utilized its possibilities? Has not the familiarity and ease with which we speak of critical changes and transformations and lay everything at their door, led us to a too easily satisfied curiosity as to their details?

If each of us has a clear mental picture of what little is known of these changes, will it not encourage more of us to seek further, to investigate further, and hence be able to add to our knowledge? There are those who are satisfied with the brief belief that when steel is heated to a certain temperature and quenched it is hardened. True as this fact is, they overlook the more important one that many steels can be heated to any one of a thousand different temperatures and will harden upon quenching. Others are satisfied with the knowledge that after quenching a given steel from a certain temperature it becomes hard, from higher temperatures it becomes harder, and finally quenched from a high enough temperature it assumes its maximum practical hardness. The explanation that the first increase in hardness is due to the pearlite carbide going into solution, the successive increases to the gradual absorption of the remaining ferrite, and the final increase to the completion of these changes, is frequently the extent of their knowledge. While this is true to the best of our present-day knowledge of the subject, it does not tell the full story in all the interesting details that actually exist in practice. We may, therefore, possibly gain a fresh view of the subject, and one with more detail, by studying the story as told by the steel itself translated by the microscope.

To accomplish this, we might choose a given analysis, determine its critical range, heat one specimen to a temperature below the range and quench, another to a slightly higher temperature and quench, and successive specimens to successively higher temperatures until we were well above the top of the range. By preparing each specimen for the microscope, we would then have a complete metallographic story of the change, each specimen constituting a chapter. A simpler method and one which gives a continuous history of the change is to heat one end of the bar of steel chosen to well above its critical range by inserting this end only in the heat and allowing the other end to remain outside the furnace and well below any critical temperature. The steel upon quenching will contain at some point a structure similar to any of the separately heat-treated samples, and will show from one end to the other of the bar a continuous record of the transformation.

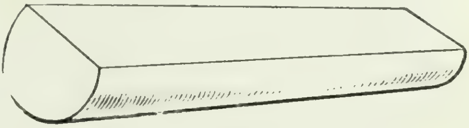


FIG. 1.

This method was followed in this instance. A piece of normalized 0.50-per-cent carbon steel 100 mm. long and 12 mm. in diameter, milled off to obtain a 7-mm. face for its full length, was chosen. See Fig. 1. One end was heated in a small bench forge to well above its critical range, while the other end outside the furnace remained well below any critical temperature. The specimen was quenched all over in cold water, and 1 mm. was then ground off to remove any possible effect of surface decarburization. This grinding was done with extreme care in order to prevent any tempering effect on the steel. The specimen was then polished and etched in a 5-per-cent solution of picric acid in absolute alcohol, and sixteen overlapping photomicrographs of one hundred diameters were taken from a point in the specimen entirely unaffected by any critical change to a point almost above the maximum effect of the critical transformation. These sixteen photomicrographs were then matched together and mounted as one photograph, approximately 117 cm. long. See Fig. 2., Plate I.[1]

Let us now study briefly some of the facts this photomicrographic history shows us. At point *A*, Fig. 2, we note that the steel has a sorbitic-pearlitic structure, characteristic of steels of this analysis after annealing or the equivalent of a too rapid normalization. This structure is shown in Fig. 3 in more detail by a higher magnification (500 diameters). We may consider point *A*, Fig. 2, and Fig. 3 as representative of the structure of this particular specimen before the heat-treatment outlined has had any practical effect upon it. The steel at this point may therefore be defined as an aggregate of ferrite grains and sorbitic pearlite grains. The former grains are homogeneous, but the latter are in themselves an aggregate.

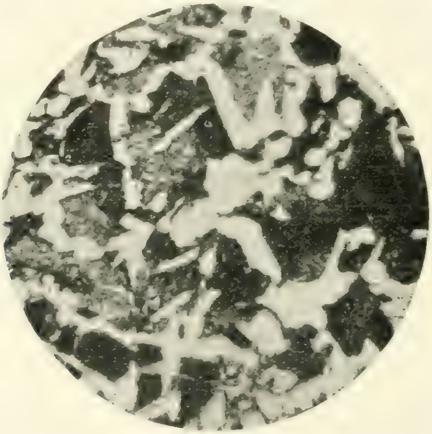
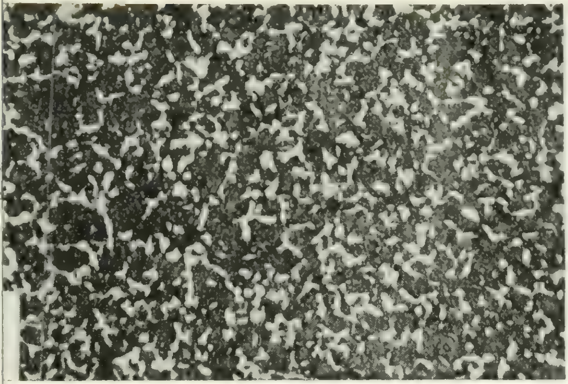


FIG. 3.—Point *A* (× 500).

---

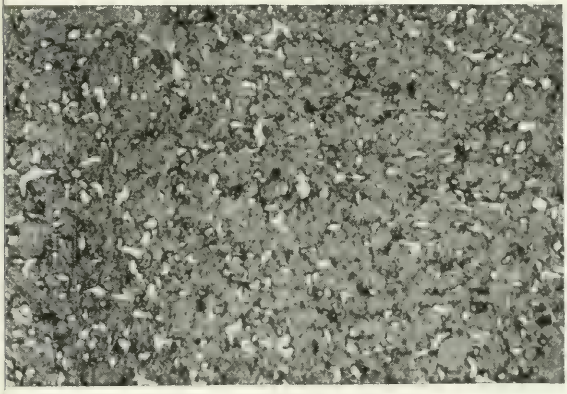
[1] On account of the extreme length of this photomicrograph, it was necessary in reproducing it to divide it into three parts.—ED.

PLATE I.
PROC. AM. SOC. TEST. MATS.
VOL. XVIII, PART II.
AYERS ON CHANGES WITHIN CRITICAL
RANGE OF STEEL.

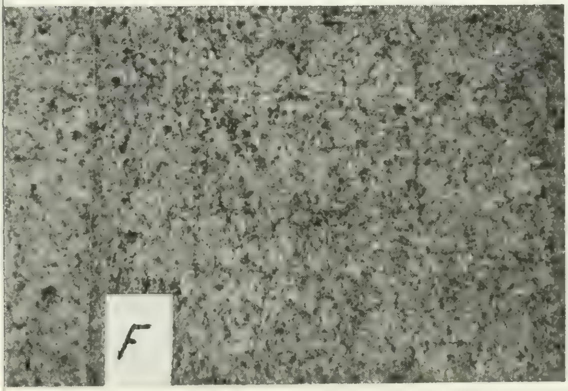


(This end b
low any critic
temperature.)

(Match with left end of next section.)



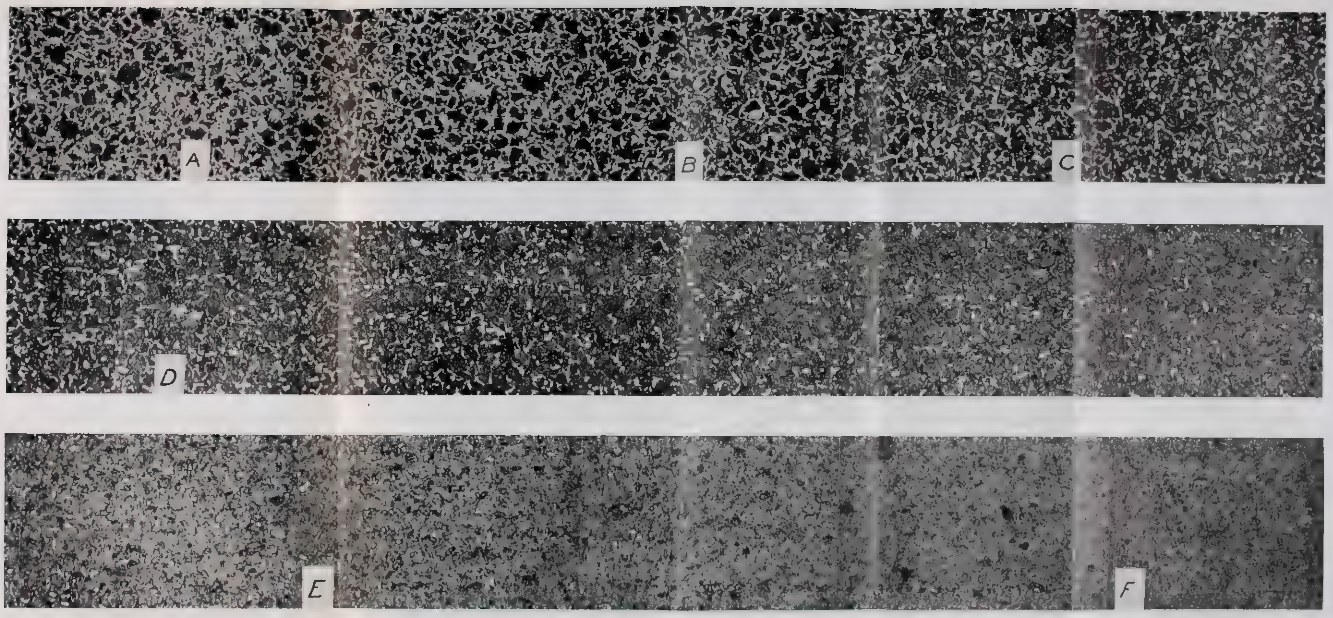
(Match with left end of next section.)



(This end heated to above Ac_{3-2}.)

PLATE I.
PROC. AM. SOC. TEST MATS.
VOL. XVIII, PART II
AYERS ON CHANGES WITHIN CRITICAL
RANGE OF STEEL

s end be-
y critical
ature.)



(Match with
left end of next
section.)

(Match with
left end of next
section.)

(This end
heated to above
$Ac_{3\text{-}2}$.)

FIG. 2.—Photomicrograph showing Microstructure resulting from Quenching a Piece of 0.50-per-cent Carbon Steel in Oil after One End (*F*) was heated above $Ac_{3\text{-}2}$ while the Other End (*A*) remained below any Critical Temperature. (×100.)
Etch = 5-per-cent Solution of Picric Acid in Absolute Alcohol.

We may consider this description to fit the average piece of steel of this analysis, as it was used in engineering practice before the full advantages of heat treatment were realized. The physical properties of the metal would naturally be a combination of the physical properties of its two constituents, ferrite or iron and sorbitic pearlite. Approximately, they would be:

Tensile strength, lb. per sq. in.	100 000
Elongation in 2 in., per cent	18
Brinell hardness	187

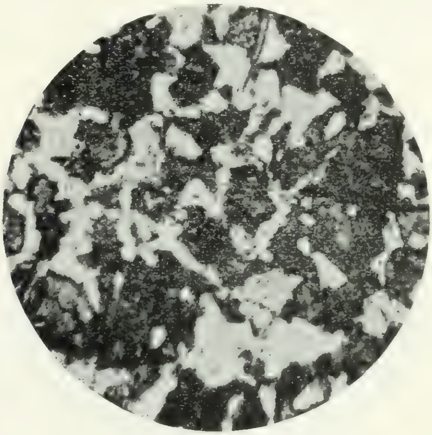


FIG. 4.—Point *B* (× 500).

Let us now examine the structure as shown in Fig. 2 a little nearer to the end of the specimen which was heated higher, and let us note the location of the structure which first shows signs of any noticeable change or transformation. At point *B*, Fig. 2, a slight change is apparent. The relative amount of ferrite remains the same, but some of the sorbitic pearlite appears to have undergone a change in the whole grain in some cases or in a portion of the grain in others. Under the microscope, this change is very apparent, due to the different colorations of the changed portions when compared with their former color. Fig. 4 shows these grains in more detail. The sorbitic pearlite has been transformed into austenite in spots, which in the quenching process is retained in the martensitic condition. It is interesting to note that these martensite grains are the result of the transformation *in situ* of the pearlite grains into the solid solution state, and they are kept after quenching in the martensitic state, so that they contain the eutectoid or maximum carbon content for the steel under discussion. It will be noticed subsequently that martensite grains formed considerably later in the transformation do not contain this maximum content of carbon. We may consider Fig. 4 as representative of the structure of a 0.50-per-cent carbon steel heated so closely to the Ac_1 point that portions of the pearlite grains have been transformed into austenite and retained as martensite, while other grains have still retained their pearlitic structure. The steel at this point is an aggregate of soft ferrite, intensely hard martensite, a small amount of troostite and sorbitic pearlite. Its properties would vary considerably with the slightest change in the quenching temperature. Theoretically at least, we would not expect to find any troostite in this case right at the Ac_1 point, but we are not quite sure that the steel at this point was heated to this temperature, so that it is very possible that some portions have been subjected to those changes which occur slightly above the Ac_1 point, namely,

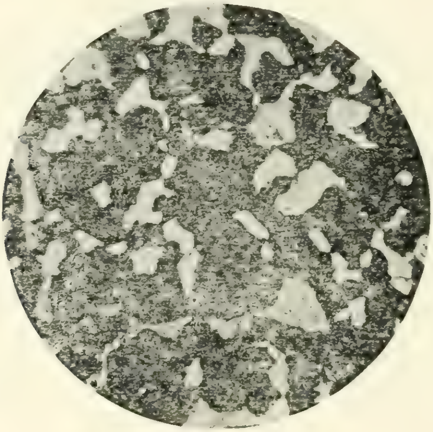


FIG. 5.—Point *C* (× 500).

the absorption of the ferrite into the martensite grains, producing a dilution of the boundary of the martensite grains in carbon content. Upon quenching, this portion of the grain, therefore, is retained in the troostitic condition rather than in the martensitic condition.

Let us now examine the structure a little further along in the transformation. The next point chosen might well be point *C*, shown in more detail by Fig. 5. At this point the quenching temperature has been high enough to result in the transformation of every grain of pearlite or sorbitic pearlite into martensite grains fringed at spots along their boundaries with troostite. This point corresponds to a temperature at which the Ac_1 changes have been completely effected. The steel consists chiefly at this point of an aggregate of ferrite and martensite. It is in other words composed of a relatively soft, weak, ductile constituent and an intensely hard, brittle one. Its physical properties would be a combination of the properties of these two constituents.

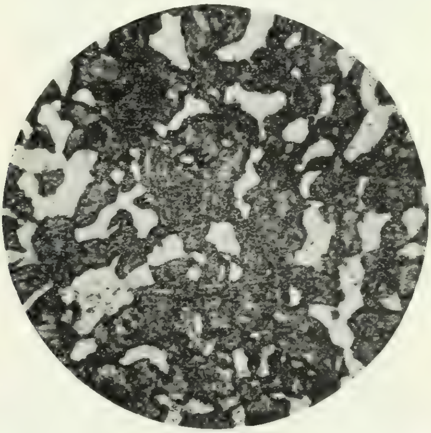


FIG. 6.—Point *D* (× 500).

The next change which we note by examining Fig. 2 still further along in the transformation is that the grains of martensite are growing in size at the expense of the ferrite grains. This change is well advanced at point *D*, shown in more detail by

Fig. 6. The ferrite is being gradually absorbed by the martensite grains, penetrating their boundary. As mentioned before, upon quenching these martensite grain boundaries have had their eutectoid carbon content so much lowered by the addition of the ferrite that the "brake action" of the carbon has only served to retain them as troostite, while the interior of the grains originally austenitic before quenching is retained as martensite. Fig. 7, at 1000 diameters, illustrates this. In other words, the martensite grains formed from quenching well above Ac_1 are lower in carbon content than those formed exactly at Ac_1 and mentioned under the discussion of point *B*. The steel at point *D* is, therefore, composed of free ferrite grains and martensite grains bordered at points by troostite. Its physical properties are a combination of the properties of these three constituents. Although the martensite grains are weaker than those martensite grains formed just above Ac_1, the steel as a whole is stronger, harder and less ductile than that formed by quenching just above Ac_1, due to the diminution in the amount of ferrite.

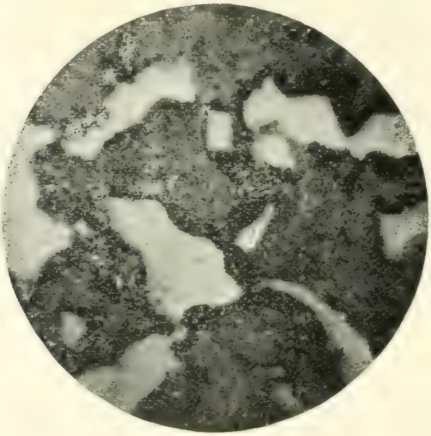


FIG. 7.—Point *D* (× 1000).

If we examine Fig. 2 still further along in the direction of the transformation, we note the only change is a gradual increase in the size of the martensite grains (and hence a lowering of their carbon content), and a diminution in the size of the ferrite grains. See Fig. 8. At point *E*, Fig. 2, shown in more detail by Fig. 9, the changes discussed are nearly completed and very little ferrite remains. At point *F*, Fig. 2, no ferrite remains but traces of troostite are still apparent. This is shown in more detail by Fig. 10.

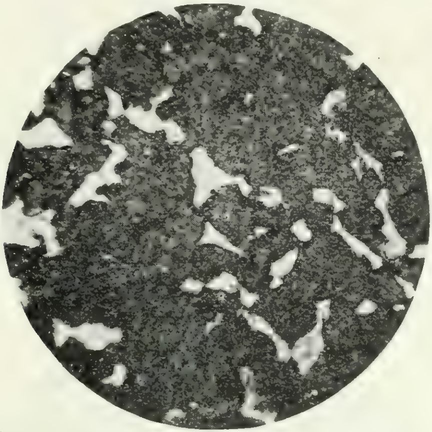


FIG. 8.—Between Points *D* and *E* (× 500).

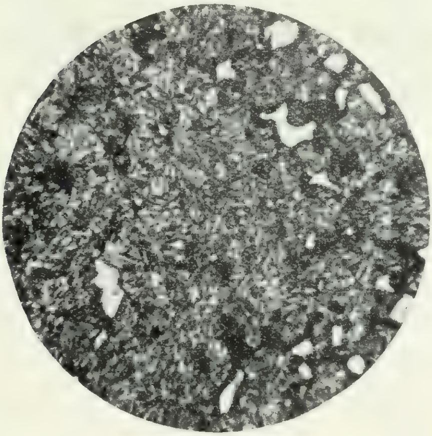


FIG. 9.—Point *E* (× 500).

At a point *G* (not shown) in the specimen far enough along in the transformation, all traces of troostite are absent and only a martensitic structure is apparent. This point was not included in Fig. 2, as it made the photomicrograph unnecessarily long. At this point, diffusion has taken place so that the carbon content of each grain of martensite is uniform throughout and all grains have the same carbon content. That is, the mass as a whole is homogeneous throughout. Diffusion no doubt occurs in the martensite grains from above the Ac_1 point, but due to the continual absorption of ferrite into the martensite grains, it has no opportunity to complete this work until the steel is at or above the Ac_{3-2} point.

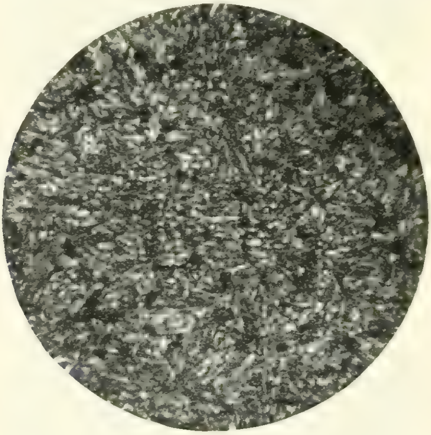


FIG. 10.—Point *F* (× 500).

Point *G* represents the structure of the steel when it is fully and perfectly hardened, the physical properties being those of martensite. Comparing them for a steel of the analysis chosen with those at point *A*, they would be approximately as follows:

	POINT *A*.	POINT *G*.
Tensile strength, lb. per sq. in.	100 000	200 000
Elongation in 2 in., per cent	18	. . .
Brinell hardness	187	550

We have observed briefly the changes in the microstructure of the steel under discussion while it has undergone a transformation that has doubled its strength and tripled its hardness. We have observed its change from an aggregate to a homogeneous mass. Its physical properties have been based upon combinations of ferrite, pearlite, sorbite, troostite and martensite. Let us bear in mind that in practice we can get any of the structures discussed and their dependent physical properties, but in general we do not want properties obtained by a change in the hardening temperature but preferably by a change in the tempering temperature. Yet there still exist cases where steel parts are quenched from a temperature within the range where a twenty-degree temperature fluctuation makes a greater variation in the physical properties of the pieces than a hundred-degree fluctuation above the top of the range. Many a so-called practical hardener is puzzled when one article is hard enough and the next too soft, due to the fact that he is not quenching from a temperature safely above the top of the critical range. Ten degrees one way or the other may mean martensite in one case and in the other ferrite, troostite and martensite. In other words, quenching in the midst of a transformation gives erratic results which do not conform to present-day requirements.

While it would be making too broad a statement to say that such inaccurate practice exists on a large scale to-day, the writer believes that investigation would show there is a needless amount of such practice, and that until the full significance and nature of the critical changes is generally known such instances are sure to exist.

CAST STEEL ANCHOR CHAIN.

By H. Jasper Cox.

SUMMARY.

Brief History of the Development.—In August, 1917, the shortage of anchor chain production was accidentally brought to the attention of the Ship Welding Sub-Committee of the General Engineering Committee of the Council of National Defense. Mr. W. L. Merrill of the General Electric Co., Chairman of the Ship Welding Sub-Committee, undertook a study of anchor chain production; while this work was going on and under date of September 13, the General Purchasing Officer of the Emergency Fleet Corporation addressed a letter to Prof. C. A. Adams, Chairman of the General Engineering Committee above mentioned, noting the deficiency of anchor chain production and asking for recommendations as to the possibility of increasing this production by the employment of electric welding.

At that time Mr. Merrill had several proposals in hand, covering:

(*a*) Straight electric welding;

(*b*) Drop forging of alternate links and electric welding of connecting links;

(*c*) Cast steel chain.

The last of these proved to be most promising and its development was rapidly pushed.

In October short lengths of cast steel chain had been produced which, on being tested at the Charleston Navy Yard, showed a much greater tensile strength than that of wrought iron chain, but with slightly less ductility. The uniformity and reliability of this chain was made possible by the employment of the electric furnace.

On October 25 a meeting was called with representatives from the Ship Welding Sub-Committee, the Classification

Societies, the Navy, the U. S. Steamboat Inspection Service, and wrought iron chain manufacturers, to discuss the merits of the cast steel chain as then developed and to determine whether it was suitable for anchor chains.

It was the general opinion that, in addition to tensile strength, toughness or resistance to shock was an extremely important feature of a satisfactory anchor chain.

It was decided at this meeting to carry out some tests to determine the comparative shock-resisting qualities of the cast steel chain and wrought iron chain. A series of shock and impact tests were then carried out by the General Electric Co. at Schenectady, and later by the National Malleable Castings Co. at Sharon, Pa.

As a result of these tests Lloyd's Register of Shipping determined to approve of the use of cast steel anchor chain in merchant vessels and immediately prepared specifications of requirements and tests for all sizes of electric cast steel anchor chain.

On March 16, 1918, these specifications were considered by the newly appointed Sub-Committee XVI, of Committee A-1, on Cast Steel Chain of this Society, and after some slight revisions were submitted to Committee A-1 for presentation to the Society at the present meeting.

CAST STEEL ANCHOR CHAIN.

BY H. JASPER COX.

INTRODUCTORY.

When riding at anchor in a tideway or in cases of emergency the safety of a vessel and lives of those on board frequently depends upon her anchor chain. For this reason too much stress cannot be laid on the importance of having these chains not only of suitable length, weight and strength for the size of the vessel, but also of great reliability.

Realizing their importance in this respect, Lloyd's Register of Shipping, as long ago as 1853, required a certificate of test for all chain cables supplied to classed vessels, and in 1868 established at their own expense a Public Proving House in England for testing cables in a licensed machine. In 1871 the British Government passed an Act in Parliament known as The Anchor and Chain Cable Act, making it compulsory to test all anchors and chains supplied to merchant vessels of British Register.

In 1858 Lloyd's Register of Shipping had specified the length, size and weight of cables required for all classed vessels of different tonnage measurement, and after 1873 these cables were tested for tensile strength in accordance with the Act. Random samples of each shot of chain were required to withstand a definite load without breaking (the Breaking Test) while every complete shot of chain, including the joining shackles, was required to be subjected to a certain proof load (the Statutory Tensile Test) without showing signs of rupture or undue strain. Similar legislation has been enacted in one or two other countries and to-day practically all of the Ship Classification Societies have adopted the same standard of requirements.

The statutory tests laid down were based on the average results obtained with good hand-made wrought iron chain. Good chain iron had a tensile strength of about 51,500 lb. per sq. in. with an elongation in 10 in. of from 23 to 30 per cent increasing with the size, and with a reduction of area of about 43 per cent.

Wrought iron chain, either hand or steam-hammer welded, has been used almost exclusively in ships to this day. Mild steel chain has been tried, but has so far proved either too ductile to retain its form under stress or too hard to ensure reliable welds.

ESSENTIAL QUALITIES IN ANCHOR CHAIN.

The essential qualities in anchor chain, in the order of their importance, may be summarized as follows:

1. Tensile Strength;
2. Weight;
3. Resistance to shock;
4. Accuracy of form of link after test;
5. Uniformity of links;
6. Resistance to wear and corrosion.

Without the weight and length to give the necessary sag and consequent spring to an outboard cable, the tensile strength required would be totally inadequate. When a vessel is riding easily there is considerable sag in her cable, and even when dragging anchor the sag is never quite taken out. It will be seen therefore that weight has an important bearing in connection with the strength.

Cables are frequently subjected to severe shocks or jerks which may be caused in a variety of ways, those more commonly experienced being:

Fast running over the wild cats;

Suddenly stopping the run of cable;

Links jambling in the chain locker or chain pipe;

Nipping at the hawse pipe (this should not happen with a properly designed lead and hawse pipe);

Nipping across the stem or bar keel when the vessel is veering in a strong tideway.

Accuracy of form and uniformity of links, including overall dimensions, are important for smooth and efficient running over the wild cats.

Resistance to wear and corrosion are important from the point of view of maintenance.

Experiments by the General Electric Co. at Schenectady.

In their first attempt to make cast steel chain, the General Electric Co. used electric furnace steel, adopting the die casting process with metal molds.

The links produced were perfectly sound and of good finish, but it was not found practicable to develop this process for commercial production for the following reasons:

(*a*) It was necessary to open the mold at a very critical time, while the metal was congealing; if left for a few seconds longer the links break due to the core being solid.

(*b*) If the mold was opened too quickly, the link being in a plastic state tended to deform.

They then made a considerable amount of chain using sand molds and cores, experimented with heat treatment and photomicrographs, and eventually obtained links which pulled at from 60 to 100 per cent above wrought iron chain. The first of these links were tested at the Bureau of Standards and some further samples were tested at a later date at the Charleston Navy Yard. In the latter tests six cast steel links 2 in. in diameter were used; three of the links had been annealed at 850° C. and cooled in the furnace, and three links had been heated to 850° C. and quenched in water.

The links were tested in an 800,000-lb. chain testing machine with the following average results:

Average of 3 Links.	Breaking Strength, lb.	Total Stretch, in.
Annealed	324 083	$1\frac{3}{16}$
Quenched	329 750	$1\frac{1}{4}$

Note.—The Breaking Test for a 2-in. wrought iron chain is 225,792 lb.

Before testing, each link was subjected to a proof stress of 145,400 lb. and none of the links showed a measurable elongation. The diameter was slightly less than 2 in. and the original length $11\frac{13}{16}$ in.

Test bars cut from the same melts and subjected to the same annealing or heat treatment showed the following results:

AVERAGE OF 3 SAMPLES.	TENSILE STRENGTH, LB. PER SQ. IN.	YIELD POINT. LB. PER SQ. IN.	ELONGATION IN 2 IN., PER CENT.	REDUCTION OF AREA, PER CENT.
Annealed	74 500	54 000	20.5	28.5
Quenched	74 450	55 300	20.8	29.9

All samples broke with 45-deg. fracture.

The chemical analysis made from composite drillings taken from the links were:

	CARBON.	MANGANESE.	PHOSPHORUS.	SULFUR.	SILICON.
Annealed links, per cent	0.32	0.55	0.034	0.025	0.14
Quenched links, per cent	0.35	0.68	0.027	0.026	0.15

The general conclusions from these tests were that the quenched link was somewhat superior to the annealed link and that the yield point of both was much in excess of that of wrought iron.

In all these links the stud was cast in.

Following this a series of comparative percussion and bend tests were carried out on separate links of cast steel and wrought iron:

(*a*) The links were dropped from a height of 35 ft. on to an iron slab.

(*b*) The links were struck end on by a weight of 3300 lb. falling from a height of 43 in. (In both of these tests links were tested at normal and at zero temperatures.)

(*c*) The links were supported at their ends and struck in the middle by the same weight and drop as in (*b*).

The general conclusion from these tests was that they had little relative value, or did not duplicate conditions met with in service.

It was then suggested that tests be devised whereby the energy absorbed in breaking the links by a sudden blow might be measured. A machine was built, and arrangements made by use of the oscillograph to do this, but great difficulty was experienced in obtaining satisfactory means of holding the couplets of chain and separate links, and no really quantitive results were obtained.

EXPERIMENTS BY THE NATIONAL MALLEABLE CASTINGS CO. AT SHARON, PA.

At this time the subject was brought to the attention of The National Malleable Castings Co. of Cleveland, who immediately saw the resemblance between the problems of cast steel anchor chain and car coupler knuckles. These knuckles not only transmit the entire tractive effort of the locomotive in pulling the train, but also receive shocks of great suddenness and intensity, both jerks and buffs, due to the surging of trains, the running out and in of "slack" during the application and release of brakes, and in coupling by impact.

Another point of similarity is the importance of the knuckle maintaining its original form without distortion under all working conditions.

After exhaustive tests and experiments some years ago this company had developed a special electric steel which combined with a high tensile strength a remarkable ability to withstand shock without distortion. This material they called "Naco" steel. They were invited to participate in the further development of cast steel chain and prepared samples of $1\frac{3}{8}$, 2, $2\frac{1}{4}$ and $2\frac{7}{8}$-in. chain, including both couplets of the common link of each size and the end combinations of special links and shackles. These samples were made of Naco steel and were tested on March 1 and 2, 1918, at their Sharon plant.

Briefly, the results may be summarized as follows:

A total of seventeen static tests and eight dynamic tests were made. The static tests covered the sizes of chain above mentioned, and were largely upon Naco cast steel chain only. The dynamic tests covered the 2-in. chain only, and included samples of commercial wrought iron chain, chain from the Charleston Navy Yard, and Naco cast steel chain. The primary purpose of these tests was to demonstrate that the Naco cast steel, when put into chain and properly heat treated, would not only give static tensile results in excess of present specified breaking loads on wrought chain, but would withstand suddenly applied shock stresses better than wrought iron chains of corresponding sizes.

Of the four different sizes of Naco chain tested statically, the $1\frac{3}{8}$-in. chain showed an average breaking load about 73 per cent above the specified breaking load of wrought chain, the 2-in. chain showed 86 per cent, the $2\frac{1}{4}$-in. showed 75 per cent, and the $2\frac{7}{8}$-in. showed 77 per cent, or an average improvement of about 78 per cent.

In the dynamic tests, consisting of tensile shock tests applied through a Master Car Builders' drop testing machine to short sample pieces of chain, the 2-in. commercial wrought iron chain in three tests averaged 142,680 ft.-lb., the Navy Yard wrought chain in two tests averaged 623,200 ft.-lb., and the Naco cast steel chain in three tests averaged 1,902,400 ft.-lb. These figures do not indicate the number of foot pounds of energy actually absorbed by each type of chain, as some of the energy was dissipated in other ways; but they may be considered as a *comparative* basis for determining the relative shock absorbing capacity of the different chains. Using the figure 1 as the basis for commercial wrought iron chain, the Navy Yard chain showed 4.3 times, and the Naco cast steel chain 13.2 times as much capacity for resisting a jerk shock of this nature.

Some further tests were carried out on April 5 at Sharon to determine the transverse strength of these links under both static and dynamic loads. In the static test individual 2-in. common links were supported on 2-in. diameter round pins spaced 8 in. center to center. A third 2-in. round pin was placed transversely across the link at its center and the load applied through this third pin, with the following results:

Wrought Iron Link, supported 8 in. Centers. Test No. 1.		"Naco" Steel Link, supported 8 in. Centers. Test No. 2.	
Load, lb.	Deflection, in.	Load, lb.	Deflection, in.
25 000	0.00	145 000	0.00
50 000	0.01	161 000	0.01
75,000	0.06	225 000	0.17
100 000	0.33		
125 000	0.83		
145 000	1.66		
Support pins slipped from under the link at 145,000 lb. load. Total number of degrees through which link bent, 53.5.		Fractured one side of link close to stud at load of 237,300 lb. Test continued and fractured remaining side at 145,000 lb. load. Section of metal through fracture shows solid.	

In the dynamic transverse test individual common links were supported in a standard M. C. B. knuckle pin test block. The supports were $\frac{3}{4}$-in. radius and 10 in. center to center, the dynamic load being applied transversely at the center of the link through a plunger having a radius at its nose of $\frac{3}{4}$ in. The results of these tests were as follows:

Test No.	Material.	Fall of 1640-lb. Tup, ft.	Deflection, deg.	Remarks.
9	Wrought Iron	6	21	No fracture.
10	" "	7	32	" "
11	" "	8	..	Link broke.
12	" "	8	36	No fracture.
13	Naco Steel	8	11	" "
14	" "	8	12	" "
15	" "	10	not measured	Link broke second blow at 10 ft.
16	" "	12	..	Link broke.

The general conclusion from these tests was that Naco cast steel chain not only fulfilled all the requirements of a good anchor chain but was supeerior to welded wrought iron chain.

The Committee of Lloyd's Register of Shipping immediately sanctioned the use of this chain on classed vessels and the Emergency Fleet Corporation have ordered a considerable quantity for their new tonnage.

METHODS OF MOLDING AND CASTING LINKS.

A number of successful molding and casting methods have been tried, by some of which alternate links are precast and inserted in the molds before casting the connecting links; in others all links may be cast at one time; while other methods again are adaptable to either.

A good deal of controversy has arisen regarding the respective merits of gating on the stud or on the side of the link, but it may be said that good links have been produced by either. The stud being the least important part of the link, any defect caused at the gate is not of the same importance as it would be on the side.

It is considered most desirable that only dry sand molds and cores be used, in order to avoid as far as possible the tendency of piping in the casting, especially in the smaller links.

HEAT TREATMENT.

The Naco cast steel links were subjected to the same heat treatment as Naco car coupler knuckles. In this treatment the links were placed on a traveller and slowly passed through a heating furnace in which the desired heat is automatically controlled by special contracting pyrometers. At the discharge end of this furnace the links are dropped into a quenching tank of water and after quenching are slowly passed through a drawing furnace on a second traveller.

For the treatment of complete lengths of 15 fathoms of cable modifications in the arrangements of these furnaces and quenching tanks will of course have to be made, but it is understood that this has already been worked out by The National Malleable Castings Co.

SPECIFICATIONS.

Following the first series of tests at Sharon, Lloyd's Register of Shipping prepared specifications of requirements for Electric Cast Steel Anchor Chain intended to be used in classed vessels, and these specifications with some slight revision have been submitted to Committee A-1 on Steel.

It was not considered desirable to lay down any specific requirements with regard to manufacture, but to commence with it was thought necessary to limit the application to the electric furnace process, to require the use of dry sand molds or cores, and to subject the chain to a heat treatment.

With regard to the physical tests, it was decided to take advantage of the higher tensile strength easily obtained in cast steel, and to specify a proof load equal to the present breaking load of wrought iron chain and a breaking load 40 per cent in excess of the present breaking load. This provided a considerable margin of safety at little or no sacrifice, since owing to the importance of weight as a factor in anchor chain it was not permissible to make a corresponding reduction in the diameter.

Sufficient data were not at hand to specify shock tests for all sizes of cable, nor was it considered necessary in the present state of the development to insist on any particular form of shock test for general application. It was therefore decided to cover this test in a general manner in the specifications, such that the Classification Societies may specify any particular crucial or commercial test considered necessary to determine the shock resisting qualities of the material.

In the case of the chain to be made by The National Malleable Castings Co., test pieces from each shot of chain manufactured will for the present be subjected to an M. C. B. drop test based on the average results obtained with good wrought iron chain of similar size.

At the time of writing this paper, further tests to secure these data for different sizes of wrought iron chain are under way.

Tables giving the weights, proof and breaking loads, standard dimensions of links and shackles, and tolerances in dimensions for all sizes of Merchant Service Anchor Chain are appended.

Acknowledgements.—In conclusion the writer desires to express his indebtedness to Professor C. A. Adams, Mr. W. L. Merrill of the General Electric Co. and Mr. Chester K. Brooks of The National Malleable Castings Co., for their kindness in supplying much of the data embodied in this paper.

APPENDIX.

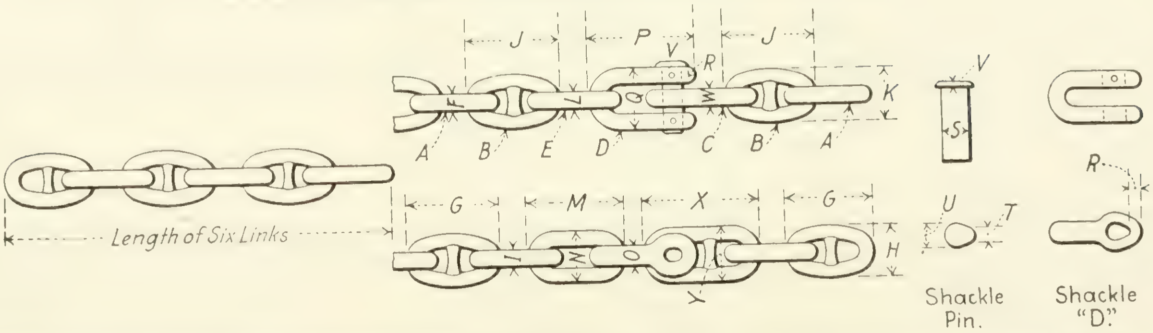
TABLE I.—WEIGHT OF CHAIN PER 15 FATHOMS.

Size of Chain, in.	Weight, lb.	Size of Chain, in.	Weight, lb.	Size of Chain, in.	Weight, lb.
$1\frac{3}{8}$	1 625	$2\frac{1}{8}$	3 785	$2\frac{7}{8}$	7 015
$1\frac{7}{16}$	1 775	$2\frac{3}{16}$	4 015	$2\frac{15}{16}$	7 330
$1\frac{1}{2}$	1 935	$2\frac{1}{4}$	4 245	3	7 650
$1\frac{9}{16}$	2 090	$2\frac{5}{16}$	4 485	$3\frac{1}{16}$	7 980
$1\frac{5}{8}$	2 235	$2\frac{3}{8}$	4 725	$3\frac{1}{8}$	8 320
$1\frac{11}{16}$	2 410	$2\frac{7}{16}$	4 960	$3\frac{3}{16}$	8 660
$1\frac{3}{4}$	2 590	$2\frac{1}{2}$	5 265	$3\frac{1}{4}$	9 010
$1\frac{13}{16}$	2 785	$2\frac{9}{16}$	5 535	$3\frac{5}{16}$	9 360
$1\frac{7}{8}$	2 975	$2\frac{5}{8}$	5 815	$3\frac{3}{8}$	9 725
$1\frac{15}{16}$	3 175	$2\frac{11}{16}$	6 105	$3\frac{7}{16}$	10 095
2	3 355	$2\frac{3}{4}$	6 405	$3\frac{1}{2}$	10 475
$2\frac{1}{16}$	3 570	$2\frac{13}{16}$	6 705	$3\frac{3}{4}$	12 025

TABLE II.—PROOF AND BREAKING LOADS FOR CHAIN.

Size of Chain, in.	Proof Test, lb.	Breaking Test, lb.	Size of Chain, in.	Proof Test, lb.	Breaking Test, lb.	Size of Chain, in.	Proof Test, lb.	Breaking Test, lb.
$1\frac{3}{8}$	114 000	160 000	$2\frac{1}{8}$	255 000	357 000	$2\frac{7}{8}$	431 500	604 000
$1\frac{7}{16}$	124 500	175 000	$2\frac{3}{16}$	270 000	378 000	$2\frac{15}{16}$	444 500	622 000
$1\frac{1}{2}$	131 500	184 000	$2\frac{1}{4}$	285 000	400 000	3	457 000	640 000
$1\frac{9}{16}$	137 500	193 000	$2\frac{5}{16}$	302 000	423 000	$3\frac{1}{16}$	469 500	658 000
$1\frac{5}{8}$	149 000	208 000	$2\frac{3}{8}$	318 500	446 000	$3\frac{1}{8}$	482 000	676 000
$1\frac{11}{16}$	160 500	225 000	$2\frac{7}{16}$	335 000	470 000	$3\frac{3}{16}$	494 500	693 000
$1\frac{3}{4}$	173 000	242 000	$2\frac{1}{2}$	353 000	494 000	$3\frac{1}{4}$	506 500	710 000
$1\frac{13}{16}$	185 500	260 000	$2\frac{9}{16}$	366 000	512 000	$3\frac{5}{16}$	518 500	726 000
$1\frac{7}{8}$	198 000	278 000	$2\frac{5}{8}$	379 000	531 000	$3\frac{3}{8}$	530 500	742 000
$1\frac{15}{16}$	211 500	296 000	$2\frac{11}{16}$	392 500	550 000	$3\frac{7}{16}$	541 500	758 000
2	226 000	316 000	$2\frac{3}{4}$	405 500	568 000	$3\frac{1}{2}$	553 000	775 000
$2\frac{1}{16}$	240 000	336 000	$2\frac{13}{16}$	418 500	586 000	$3\frac{3}{4}$	588 500	824 000

TABLE III.—STANDARD DIMENSIONS OF STUD LINK CHAIN CABLES.



Length of Six Links.	Common Links "A."			Enlarged Links "B."			End Links "E."			End Links "C."			Shackles "D."				Shackle Pins.			
	Size of Iron (F), in.	Outside Length (G), in.	Outside Width (H), in.	Size of Iron (I), in.	Outside Length (J), in.	Outside Width (K), in.	Size of Iron (L), in.	Outside Length (M), in.	Outside Width (N), in.	Size of Iron (W), in.	Outside Length (X), in.	Outside Width (Y), in.	Size of Iron (O), in.	Outside Length (P), in.	Outside Width (Q), in.	(R), in.	(S), in.	(T), in.	(U), in.	(V), in.
8 ft. 8 in.	4	24	$14\frac{3}{8}$	$4\frac{1}{4}$	$25\frac{1}{2}$	$15\frac{1}{8}$	$4\frac{1}{2}$	$25\frac{1}{2}$	16	$4\frac{1}{2}$	$30\frac{1}{8}$	16	$4\frac{1}{2}$	$25\frac{7}{8}$	16	$3\frac{1}{4}$	$6\frac{1}{2}$	4	$4\frac{3}{4}$	$\frac{3}{4}$
8 " $1\frac{1}{2}$ "	$3\frac{3}{4}$	$22\frac{1}{2}$	$13\frac{1}{2}$	4	$23\frac{7}{8}$	$14\frac{3}{16}$	$4\frac{1}{4}$	$23\frac{7}{8}$	15	$4\frac{1}{4}$	$28\frac{1}{4}$	15	$4\frac{1}{4}$	$24\frac{1}{4}$	15	$3\frac{1}{16}$	$6\frac{1}{8}$	$3\frac{3}{4}$	$4\frac{7}{16}$	$\frac{11}{16}$
7 " 7 "	$3\frac{1}{2}$	21	$12\frac{5}{8}$	$3\frac{3}{4}$	$22\frac{5}{16}$	$13\frac{1}{4}$	$3\frac{15}{16}$	$22\frac{5}{16}$	14	$3\frac{15}{16}$	$26\frac{3}{8}$	14	$3\frac{15}{16}$	$22\frac{5}{8}$	14	$2\frac{7}{8}$	$5\frac{11}{16}$	$3\frac{1}{2}$	$4\frac{3}{16}$	$\frac{11}{16}$
7 " $5\frac{3}{8}$ "	$3\frac{7}{16}$	$20\frac{5}{8}$	$12\frac{3}{8}$	$3\frac{5}{8}$	$21\frac{15}{16}$	13	$3\frac{7}{8}$	$21\frac{15}{16}$	$13\frac{3}{4}$	$3\frac{7}{8}$	$25\frac{15}{16}$	$13\frac{3}{4}$	$3\frac{7}{8}$	$22\frac{1}{4}$	$13\frac{3}{4}$	$2\frac{13}{16}$	$5\frac{9}{16}$	$3\frac{7}{16}$	$4\frac{1}{16}$	$\frac{5}{8}$
7 " $3\frac{3}{4}$ "	$3\frac{3}{8}$	$20\frac{1}{4}$	$12\frac{1}{8}$	$3\frac{9}{16}$	$21\frac{1}{2}$	$12\frac{3}{4}$	$3\frac{13}{16}$	$21\frac{1}{2}$	$13\frac{1}{2}$	$3\frac{13}{16}$	$25\frac{7}{16}$	$13\frac{1}{2}$	$3\frac{13}{16}$	$21\frac{13}{16}$	$13\frac{1}{2}$	$2\frac{3}{4}$	$5\frac{1}{2}$	$3\frac{3}{8}$	4	$\frac{5}{8}$
7 " $2\frac{1}{8}$ "	$3\frac{5}{16}$	$19\frac{7}{8}$	$11\frac{15}{16}$	$3\frac{1}{2}$	$21\frac{1}{8}$	$12\frac{1}{2}$	$3\frac{3}{4}$	$21\frac{1}{8}$	$13\frac{1}{4}$	$3\frac{3}{4}$	$24\frac{15}{16}$	$13\frac{1}{4}$	$3\frac{3}{4}$	$21\frac{7}{16}$	$13\frac{1}{4}$	$2\frac{11}{16}$	$5\frac{3}{8}$	$3\frac{5}{16}$	$3\frac{15}{16}$	$\frac{5}{8}$
7 " $0\frac{1}{2}$ "	$3\frac{1}{4}$	$19\frac{1}{2}$	$11\frac{11}{16}$	$3\frac{7}{16}$	$20\frac{3}{4}$	$12\frac{1}{4}$	$3\frac{5}{8}$	$20\frac{3}{4}$	13	$3\frac{5}{8}$	$24\frac{1}{2}$	13	$3\frac{5}{8}$	21	13	$2\frac{5}{8}$	$5\frac{5}{16}$	$3\frac{1}{4}$	$3\frac{7}{8}$	$\frac{5}{8}$

NOTE.—Particular attention is directed to the following:
1. It is important that the above dimensions be strickly adhered to.
2. To insure the shackles all leading the same way over the windlass, it is necessary that there be an odd number of links in each length of cable.

TABLE III.—STANDARD DIMENSIONS OF STUD LINK CHAIN CABLES.—*Continued*

Length of Six Links.	Common Links "A."			Enlarged Links "B."			End Links "E."			End Links "C."			Shackles "D."				Shackle Pins.			
	Size of Iron (F), in.	Outside Length (G), in.	Outside Width (H), in.	Size of Iron (I), in.	Outside Length (J), in.	Outside Width (K), in.	Size of Iron (L), in.	Outside Length (M), in.	Outside Width (N), in.	Size of Iron (W), in.	Outside Length (X), in.	Outside Width (Y), in.	Size of Iron (O), in.	Outside Length (P), in.	Outside Width (Q), in.	(R), in.	(S), in.	(T), in.	(U), in.	(V), in.
6 " $10\frac{7}{8}$ "	$3\frac{3}{16}$	$19\frac{1}{8}$	$11\frac{1}{2}$	$3\frac{3}{8}$	$20\frac{5}{16}$	$12\frac{1}{16}$	$3\frac{9}{16}$	$20\frac{5}{16}$	$12\frac{3}{4}$	$3\frac{9}{16}$	24	$12\frac{3}{4}$	$3\frac{9}{16}$	$20\frac{5}{8}$	$12\frac{3}{4}$	$2\frac{9}{16}$	$5\frac{3}{16}$	$3\frac{3}{16}$	$3\frac{13}{16}$	$\frac{5}{8}$
6 " $9\frac{1}{4}$ "	$3\frac{1}{8}$	$18\frac{3}{4}$	$11\frac{1}{4}$	$3\frac{5}{16}$	$19\frac{15}{16}$	$11\frac{13}{16}$	$3\frac{1}{2}$	$19\frac{15}{16}$	$12\frac{1}{2}$	$3\frac{1}{2}$	$23\frac{9}{16}$	$12\frac{1}{2}$	$3\frac{1}{2}$	$20\frac{1}{4}$	$12\frac{1}{2}$	$2\frac{9}{16}$	$5\frac{1}{16}$	$3\frac{1}{8}$	$3\frac{11}{16}$	$\frac{9}{16}$
6 " $7\frac{5}{8}$ "	$3\frac{1}{16}$	$18\frac{3}{8}$	11	$3\frac{1}{4}$	$19\frac{1}{2}$	$11\frac{5}{16}$	$3\frac{7}{16}$	$19\frac{1}{2}$	$12\frac{1}{4}$	$3\frac{7}{16}$	$23\frac{1}{16}$	$12\frac{1}{4}$	$3\frac{7}{16}$	$19\frac{13}{16}$	$12\frac{1}{4}$	$2\frac{1}{2}$	5	$3\frac{1}{16}$	$3\frac{5}{8}$	$\frac{9}{16}$
6 " 6 "	3	18	$10\frac{13}{16}$	$3\frac{3}{16}$	$19\frac{1}{8}$	$11\frac{3}{8}$	$3\frac{3}{8}$	$19\frac{1}{8}$	12	$3\frac{3}{8}$	$22\frac{5}{8}$	12	$3\frac{3}{8}$	$19\frac{7}{16}$	12	$2\frac{7}{16}$	$4\frac{7}{8}$	3	$3\frac{9}{16}$	$\frac{9}{16}$
6 " $4\frac{3}{8}$ "	$2\frac{15}{16}$	$17\frac{5}{8}$	$10\frac{9}{16}$	$3\frac{1}{8}$	$18\frac{3}{4}$	$11\frac{1}{8}$	$3\frac{5}{16}$	$18\frac{3}{4}$	$11\frac{3}{4}$	$3\frac{5}{16}$	$22\frac{1}{8}$	$11\frac{3}{4}$	$3\frac{5}{16}$	19	$11\frac{3}{4}$	$2\frac{3}{8}$	$4\frac{3}{4}$	$2\frac{15}{16}$	$3\frac{1}{2}$	$\frac{9}{16}$
6 " $2\frac{3}{4}$ "	$2\frac{7}{8}$	$17\frac{1}{4}$	$10\frac{3}{8}$	$3\frac{1}{16}$	$18\frac{5}{16}$	$10\frac{7}{8}$	$3\frac{1}{4}$	$18\frac{5}{16}$	$11\frac{1}{2}$	$3\frac{1}{4}$	$21\frac{11}{16}$	$11\frac{1}{2}$	$3\frac{1}{4}$	$18\frac{5}{8}$	$11\frac{1}{2}$	$2\frac{5}{16}$	$4\frac{11}{16}$	$2\frac{7}{8}$	$3\frac{7}{16}$	$\frac{9}{16}$
6 " $1\frac{1}{8}$ "	$2\frac{13}{16}$	$16\frac{7}{8}$	$10\frac{1}{8}$	3	$17\frac{15}{16}$	$10\frac{5}{8}$	$3\frac{3}{16}$	$17\frac{15}{16}$	$11\frac{1}{4}$	$3\frac{3}{16}$	$21\frac{3}{16}$	$11\frac{1}{4}$	$3\frac{3}{16}$	$18\frac{3}{16}$	$11\frac{1}{4}$	$2\frac{5}{16}$	$4\frac{9}{16}$	$2\frac{13}{16}$	$3\frac{5}{16}$	$\frac{1}{2}$
5 " $11\frac{1}{2}$ "	$2\frac{3}{4}$	$16\frac{1}{2}$	$9\frac{7}{8}$	$2\frac{15}{16}$	$17\frac{9}{16}$	$10\frac{3}{8}$	$3\frac{1}{8}$	$17\frac{9}{16}$	11	$3\frac{1}{8}$	$20\frac{3}{4}$	11	$3\frac{1}{8}$	$17\frac{13}{16}$	11	$2\frac{1}{4}$	$4\frac{1}{2}$	$2\frac{3}{4}$	$3\frac{1}{4}$	$\frac{1}{2}$
5 " $9\frac{7}{8}$ "	$2\frac{11}{16}$	$16\frac{1}{8}$	$9\frac{11}{16}$	$2\frac{7}{8}$	$17\frac{1}{8}$	$10\frac{1}{8}$	3	$17\frac{1}{8}$	$10\frac{3}{4}$	3	$20\frac{1}{4}$	$10\frac{3}{4}$	3	$17\frac{3}{8}$	$10\frac{3}{4}$	$2\frac{3}{16}$	$4\frac{3}{8}$	$2\frac{11}{16}$	$3\frac{3}{16}$	$\frac{1}{2}$
5 " $8\frac{1}{4}$ "	$2\frac{5}{8}$	$15\frac{3}{4}$	$9\frac{7}{16}$	$2\frac{13}{16}$	$16\frac{3}{4}$	$9\frac{15}{16}$	$2\frac{15}{16}$	$16\frac{3}{4}$	$10\frac{1}{2}$	$2\frac{15}{16}$	$19\frac{3}{4}$	$10\frac{1}{2}$	$2\frac{15}{16}$	17	$10\frac{1}{2}$	$2\frac{1}{8}$	$4\frac{1}{4}$	$2\frac{5}{8}$	$3\frac{1}{8}$	$\frac{1}{2}$
5 " $6\frac{5}{8}$ "	$2\frac{9}{16}$	$15\frac{3}{8}$	$9\frac{1}{4}$	$2\frac{3}{4}$	$16\frac{5}{16}$	$9\frac{11}{16}$	$2\frac{7}{8}$	$16\frac{5}{16}$	$10\frac{1}{4}$	$2\frac{7}{8}$	$19\frac{5}{16}$	$10\frac{1}{4}$	$2\frac{7}{8}$	$16\frac{9}{16}$	$10\frac{1}{4}$	$2\frac{1}{8}$	$4\frac{3}{16}$	$2\frac{9}{16}$	$3\frac{1}{16}$	$\frac{1}{2}$
5 " 5 "	$2\frac{1}{2}$	15	9	$2\frac{5}{8}$	$15\frac{15}{16}$	$9\frac{7}{16}$	$2\frac{13}{16}$	$15\frac{15}{16}$	10	$2\frac{13}{16}$	$18\frac{7}{8}$	10	$2\frac{13}{16}$	$16\frac{3}{16}$	10	$2\frac{1}{16}$	$4\frac{1}{16}$	$2\frac{1}{2}$	3	$\frac{1}{2}$
5 " $3\frac{3}{8}$ "	$2\frac{7}{16}$	$14\frac{5}{8}$	$8\frac{3}{4}$	$2\frac{9}{16}$	$15\frac{9}{16}$	$9\frac{3}{16}$	$2\frac{3}{4}$	$15\frac{9}{16}$	$9\frac{3}{4}$	$2\frac{3}{4}$	$18\frac{3}{8}$	$9\frac{3}{4}$	$2\frac{3}{4}$	$15\frac{3}{4}$	$9\frac{3}{4}$	2	$3\frac{15}{16}$	$2\frac{7}{16}$	$2\frac{7}{8}$	$\frac{7}{16}$
5 " $1\frac{3}{4}$ "	$2\frac{3}{8}$	$14\frac{1}{4}$	$8\frac{9}{16}$	$2\frac{1}{2}$	$15\frac{3}{16}$	9	$2\frac{11}{16}$	$15\frac{3}{16}$	$9\frac{1}{2}$	$2\frac{11}{16}$	$17\frac{7}{8}$	$9\frac{1}{2}$	$2\frac{11}{16}$	$15\frac{3}{8}$	$9\frac{1}{2}$	$1\frac{15}{16}$	$3\frac{7}{8}$	$2\frac{3}{8}$	$2\frac{13}{16}$	$\frac{7}{16}$
5 " $0\frac{1}{8}$ "	$2\frac{5}{16}$	$13\frac{7}{8}$	$8\frac{5}{16}$	$2\frac{7}{16}$	$14\frac{3}{4}$	$8\frac{3}{4}$	$2\frac{5}{8}$	$14\frac{3}{4}$	$9\frac{1}{4}$	$2\frac{5}{8}$	$17\frac{7}{16}$	$9\frac{1}{4}$	$2\frac{5}{8}$	$14\frac{15}{16}$	$9\frac{1}{4}$	$1\frac{7}{8}$	$3\frac{3}{4}$	$2\frac{5}{16}$	$2\frac{3}{4}$	$\frac{7}{16}$
4 " $10\frac{1}{2}$ "	$2\frac{1}{4}$	$13\frac{1}{2}$	$8\frac{1}{8}$	$2\frac{3}{8}$	$14\frac{3}{8}$	$8\frac{1}{2}$	$2\frac{9}{16}$	$14\frac{3}{8}$	9	$2\frac{9}{16}$	$16\frac{15}{16}$	9	$2\frac{9}{16}$	$14\frac{9}{16}$	9	$1\frac{13}{16}$	$3\frac{11}{16}$	$2\frac{1}{4}$	$2\frac{11}{16}$	$\frac{7}{16}$
4 " $8\frac{7}{8}$ "	$2\frac{3}{16}$	$13\frac{1}{8}$	$7\frac{7}{8}$	$2\frac{5}{16}$	$13\frac{15}{16}$	$8\frac{1}{4}$	$2\frac{7}{16}$	$13\frac{15}{16}$	$8\frac{3}{4}$	$2\frac{7}{16}$	$16\frac{1}{2}$	$8\frac{3}{4}$	$2\frac{7}{16}$	$14\frac{3}{16}$	$8\frac{3}{4}$	$1\frac{3}{4}$	$3\frac{9}{16}$	$2\frac{3}{16}$	$2\frac{5}{8}$	$\frac{7}{16}$
4 " $7\frac{1}{4}$ "	$2\frac{1}{8}$	$12\frac{3}{4}$	$7\frac{5}{8}$	$2\frac{1}{4}$	$13\frac{1}{2}$	8	$2\frac{3}{8}$	$13\frac{1}{2}$	$8\frac{1}{2}$	$2\frac{3}{8}$	16	$8\frac{1}{2}$	$2\frac{3}{8}$	$13\frac{3}{4}$	$8\frac{1}{2}$	$1\frac{3}{4}$	$3\frac{7}{16}$	$2\frac{1}{8}$	$2\frac{1}{2}$	$\frac{3}{8}$
4 " $5\frac{5}{8}$ "	$2\frac{1}{16}$	$12\frac{3}{8}$	$7\frac{7}{16}$	$2\frac{3}{16}$	$13\frac{1}{8}$	$7\frac{13}{16}$	$2\frac{5}{16}$	$13\frac{1}{8}$	$8\frac{1}{4}$	$2\frac{5}{16}$	$15\frac{9}{16}$	$8\frac{1}{4}$	$2\frac{5}{16}$	$13\frac{3}{8}$	$8\frac{1}{4}$	$1\frac{11}{16}$	$3\frac{3}{8}$	$2\frac{1}{16}$	$2\frac{7}{16}$	$\frac{3}{8}$
4 ft. 4 "	2	12	$7\frac{3}{16}$	$2\frac{1}{8}$	$12\frac{3}{4}$	$7\frac{9}{16}$	$2\frac{1}{4}$	$12\frac{3}{4}$	8	$2\frac{1}{4}$	$15\frac{1}{16}$	8	$2\frac{1}{4}$	$12\frac{15}{16}$	8	$1\frac{5}{8}$	$3\frac{1}{4}$	2	$2\frac{3}{8}$	$\frac{3}{8}$
4 " $2\frac{3}{8}$ "	$1\frac{15}{16}$	$1\frac{5}{8}1$	7	$2\frac{1}{16}$	$12\frac{3}{8}$	$7\frac{5}{16}$	$2\frac{3}{16}$	$12\frac{3}{8}$	$7\frac{3}{4}$	$2\frac{3}{16}$	$14\frac{5}{8}$	$7\frac{3}{4}$	$2\frac{3}{16}$	$12\frac{9}{16}$	$7\frac{3}{4}$	$1\frac{9}{16}$	$3\frac{1}{8}$	$1\frac{15}{16}$	$2\frac{5}{16}$	$\frac{3}{8}$
4 " $0\frac{3}{4}$ "	$1\frac{7}{8}$	$11\frac{1}{4}$	$6\frac{3}{4}$	2	$11\frac{15}{16}$	$7\frac{1}{16}$	$2\frac{1}{8}$	$11\frac{15}{16}$	$7\frac{1}{2}$	$2\frac{1}{8}$	$14\frac{1}{8}$	$7\frac{1}{2}$	$2\frac{1}{8}$	$12\frac{1}{8}$	$7\frac{1}{2}$	$1\frac{1}{2}$	$3\frac{1}{16}$	$1\frac{7}{8}$	$2\frac{1}{4}$	$\frac{3}{8}$

NOTE.—Particular attention is directed to the following:
1. It is important that the above dimensions be strictly adhered to.
2. To insure the shackles all leading the same way over the windlass, it is necessary that there be an odd number of links in each length of cable.

TABLE III.—STANDARD DIMENSIONS OF STUD LINK CHAIN CABLES.—*Continued.*

Length of Six Links.	Common Links "A."			Enlarged Links "B."			End Links "E."			End Links "C."			Shackles "D."				Shackle Pins.			
	Size of Iron (F), in.	Outside Length (G), in.	Outside Width (H), in.	Size of Iron (I), in.	Outside Length (J), in.	Outside Width (K), in.	Size of Iron (L), in.	Outside Lenth (M), in.	Outside Width (N), in.	Size of Iron (W), in.	Outside Length (X), in.	Outside Width (Y), in.	Size of Iron (O), in.	Outside Length (P), in.	Outside Width (Q), in.	(R), in.	(S), in.	(T), in.	(U), in.	(V), in.
3 " $11\frac{1}{8}$ in	$1\frac{13}{16}$	$10\frac{7}{8}$	$6\frac{1}{2}$	$1\frac{15}{16}$	$11\frac{9}{16}$	$6\frac{7}{8}$	$2\frac{1}{16}$	$11\frac{9}{16}$	$7\frac{1}{4}$	$2\frac{1}{16}$	$13\frac{11}{16}$	$7\frac{1}{4}$	$2\frac{1}{16}$	$11\frac{3}{4}$	$7\frac{1}{4}$	$1\frac{1}{2}$	$2\frac{15}{16}$	$1\frac{13}{16}$	$2\frac{1}{8}$	$\frac{5}{16}$
3 " $9\frac{1}{2}$ "	$1\frac{3}{4}$	$10\frac{1}{2}$	$6\frac{5}{16}$	$1\frac{7}{8}$	$11\frac{1}{8}$	$6\frac{5}{8}$	2	$11\frac{1}{8}$	7	2	$13\frac{3}{16}$	7	2	$11\frac{5}{16}$	7	$1\frac{7}{16}$	$2\frac{7}{8}$	$1\frac{3}{4}$	$2\frac{1}{16}$	$\frac{5}{16}$
3 " $7\frac{7}{8}$ "	$1\frac{11}{16}$	$10\frac{1}{8}$	$6\frac{1}{16}$	$1\frac{13}{16}$	$10\frac{3}{4}$	$6\frac{3}{8}$	$1\frac{7}{8}$	$10\frac{3}{4}$	$6\frac{3}{4}$	$1\frac{7}{8}$	$12\frac{3}{4}$	$6\frac{3}{4}$	$1\frac{7}{8}$	$10\frac{15}{16}$	$6\frac{3}{4}$	$1\frac{3}{8}$	$2\frac{3}{4}$	$1\frac{11}{16}$	2	$\frac{5}{16}$
3 " $6\frac{1}{4}$ "	$1\frac{5}{8}$	$9\frac{3}{4}$	$5\frac{7}{8}$	$1\frac{3}{4}$	$10\frac{3}{8}$	$6\frac{1}{8}$	$1\frac{13}{16}$	$10\frac{3}{8}$	$6\frac{1}{2}$	$1\frac{13}{16}$	$12\frac{1}{4}$	$6\frac{1}{2}$	$1\frac{13}{16}$	$10\frac{1}{2}$	$6\frac{1}{2}$	$1\frac{5}{16}$	$2\frac{5}{8}$	$1\frac{5}{8}$	$1\frac{15}{16}$	$\frac{5}{16}$
3 " $4\frac{5}{8}$ "	$1\frac{9}{16}$	$9\frac{3}{8}$	$5\frac{5}{8}$	$1\frac{11}{16}$	$9\frac{15}{16}$	$5\frac{7}{8}$	$1\frac{3}{4}$	$9\frac{15}{16}$	$6\frac{1}{4}$	$1\frac{3}{4}$	$11\frac{3}{4}$	$6\frac{1}{4}$	$1\frac{3}{4}$	$10\frac{1}{8}$	$6\frac{1}{4}$	$1\frac{1}{4}$	$2\frac{9}{16}$	$1\frac{9}{16}$	$1\frac{7}{8}$	$\frac{5}{16}$
3 " 3 "	$1\frac{1}{2}$	9	$5\frac{3}{8}$	$1\frac{9}{16}$	$9\frac{9}{16}$	$5\frac{11}{16}$	$1\frac{11}{16}$	$9\frac{9}{16}$	6	$1\frac{11}{16}$	$11\frac{5}{16}$	6	$1\frac{11}{16}$	$9\frac{11}{16}$	6	$1\frac{1}{4}$	$2\frac{7}{16}$	$1\frac{1}{2}$	$1\frac{13}{16}$	$\frac{5}{16}$
3 " $1\frac{3}{8}$ "	$1\frac{7}{16}$	$8\frac{5}{8}$	$5\frac{3}{16}$	$1\frac{1}{2}$	$9\frac{3}{16}$	$5\frac{7}{16}$	$1\frac{5}{8}$	$9\frac{3}{16}$	$5\frac{3}{4}$	$1\frac{5}{8}$	$10\frac{7}{8}$	$5\frac{3}{4}$	$1\frac{5}{8}$	$9\frac{5}{16}$	$5\frac{3}{4}$	$1\frac{3}{16}$	$2\frac{5}{16}$	$1\frac{7}{16}$	$1\frac{11}{16}$	$\frac{1}{4}$
2 " $11\frac{3}{4}$ "	$1\frac{3}{8}$	$8\frac{1}{4}$	$4\frac{15}{16}$	$1\frac{7}{16}$	$8\frac{3}{4}$	$5\frac{3}{16}$	$1\frac{9}{16}$	$8\frac{3}{4}$	$5\frac{1}{2}$	$1\frac{9}{16}$	$10\frac{3}{8}$	$5\frac{1}{2}$	$1\frac{9}{16}$	$8\frac{15}{16}$	$5\frac{1}{2}$	$1\frac{1}{8}$	$2\frac{1}{4}$	$1\frac{3}{8}$	$1\frac{5}{8}$	$\frac{1}{4}$
2 " $10\frac{1}{8}$ "	$1\frac{5}{16}$	$7\frac{7}{8}$	$4\frac{3}{4}$	$1\frac{3}{8}$	$8\frac{3}{8}$	$4\frac{15}{16}$	$1\frac{1}{2}$	$8\frac{3}{8}$	$5\frac{1}{4}$	$1\frac{1}{2}$	$9\frac{7}{8}$	$5\frac{1}{4}$	$1\frac{1}{2}$	$8\frac{1}{2}$	$5\frac{1}{4}$	$1\frac{1}{16}$	$2\frac{1}{8}$	$1\frac{5}{16}$	$1\frac{9}{16}$	$\frac{1}{4}$
2 " $8\frac{1}{2}$ "	$1\frac{1}{4}$	$7\frac{1}{2}$	$4\frac{1}{2}$	$1\frac{5}{16}$	$7\frac{15}{16}$	$4\frac{3}{4}$	$1\frac{7}{16}$	$7\frac{15}{16}$	5	$1\frac{7}{16}$	$9\frac{7}{16}$	5	$1\frac{7}{16}$	$8\frac{1}{8}$	5	1	2	$1\frac{1}{4}$	$1\frac{1}{2}$	$\frac{1}{4}$
2 " $6\frac{7}{8}$ "	$1\frac{3}{16}$	$7\frac{1}{8}$	$4\frac{1}{4}$	$1\frac{1}{4}$	$7\frac{9}{16}$	$4\frac{1}{2}$	$1\frac{3}{8}$	$7\frac{9}{16}$	$4\frac{3}{4}$	$1\frac{3}{8}$	$8\frac{15}{16}$	$4\frac{3}{4}$	$1\frac{3}{8}$	$7\frac{11}{16}$	$4\frac{3}{4}$	$\frac{15}{16}$	$1\frac{15}{16}$	$1\frac{3}{16}$	$1\frac{7}{16}$	$\frac{1}{4}$
2 " $5\frac{1}{4}$ "	$1\frac{1}{8}$	$6\frac{3}{4}$	4	$1\frac{3}{16}$	$7\frac{3}{16}$	$4\frac{1}{4}$	$1\frac{1}{4}$	$7\frac{3}{16}$	$4\frac{1}{2}$	$1\frac{1}{4}$	$8\frac{1}{2}$	$4\frac{1}{2}$	$1\frac{1}{4}$	$7\frac{5}{16}$	$4\frac{1}{2}$	$\frac{15}{16}$	$1\frac{13}{16}$	$1\frac{1}{8}$	$1\frac{5}{16}$	$\frac{3}{16}$
2 " $3\frac{5}{8}$ "	$1\frac{1}{16}$	$6\frac{3}{8}$	$3\frac{3}{4}$	$1\frac{1}{8}$	$6\frac{3}{4}$	4	$1\frac{3}{16}$	$6\frac{3}{4}$	$4\frac{1}{4}$	$1\frac{3}{16}$	8	$4\frac{1}{4}$	$1\frac{3}{16}$	$6\frac{7}{8}$	$4\frac{1}{4}$	$\frac{7}{8}$	$1\frac{3}{4}$	$1\frac{1}{16}$	$1\frac{1}{4}$	$\frac{3}{16}$
2 " 2 "	1	6	$3\frac{9}{16}$	$1\frac{1}{16}$	$6\frac{3}{8}$	$3\frac{3}{4}$	$1\frac{1}{8}$	$6\frac{3}{8}$	4	$1\frac{1}{8}$	$7\frac{9}{16}$	4	$1\frac{1}{8}$	$6\frac{1}{2}$	4	$\frac{13}{16}$	$1\frac{5}{8}$	1	$1\frac{3}{16}$	$\frac{3}{16}$
2 " $0\frac{3}{8}$ "	$\frac{15}{16}$	$5\frac{7}{8}$	$3\frac{5}{16}$	1	6	$3\frac{9}{16}$	$1\frac{1}{16}$	6	$3\frac{3}{4}$	$1\frac{1}{16}$	$7\frac{1}{16}$	$3\frac{3}{4}$	$1\frac{1}{16}$	$6\frac{1}{16}$	$3\frac{3}{4}$	$\frac{3}{4}$	$1\frac{1}{2}$	$\frac{15}{16}$	$1\frac{1}{8}$	$\frac{3}{16}$
1 " $10\frac{3}{4}$ "	$\frac{7}{8}$	$5\frac{1}{4}$	$3\frac{1}{8}$	$\frac{15}{16}$	$5\frac{9}{16}$	$3\frac{5}{16}$	1	$5\frac{9}{16}$	$3\frac{1}{2}$	1	$6\frac{9}{16}$	$3\frac{1}{2}$	1	$5\frac{11}{16}$	$3\frac{1}{2}$	$\frac{11}{16}$	$1\frac{7}{16}$	$\frac{7}{8}$	$1\frac{1}{16}$	$\frac{3}{16}$
1 " $9\frac{1}{8}$ "	$\frac{13}{16}$	$4\frac{7}{8}$	$2\frac{7}{8}$	$\frac{7}{8}$	$5\frac{3}{16}$	$3\frac{1}{16}$	$\frac{15}{16}$	$5\frac{3}{16}$	$3\frac{1}{4}$	$\frac{15}{16}$	$6\frac{1}{8}$	$3\frac{1}{4}$	$\frac{15}{16}$	$5\frac{1}{4}$	$3\frac{1}{4}$	$\frac{11}{16}$	$1\frac{5}{16}$	$\frac{13}{16}$	$\frac{15}{16}$	$\frac{1}{8}$
1 " $7\frac{1}{2}$ "	$\frac{3}{4}$	$4\frac{1}{2}$	$2\frac{5}{8}$	$\frac{13}{16}$	$4\frac{3}{4}$	$2\frac{13}{16}$	$\frac{7}{8}$	$4\frac{3}{4}$	3	$\frac{7}{8}$	$5\frac{5}{8}$	3	$\frac{7}{8}$	$4\frac{7}{8}$	3	$\frac{5}{8}$	$1\frac{1}{4}$	$\frac{3}{4}$	$\frac{7}{8}$	$\frac{1}{8}$
1 " $5\frac{7}{8}$ "	$\frac{11}{16}$	$4\frac{1}{8}$	$2\frac{7}{16}$	$\frac{3}{4}$	$4\frac{3}{8}$	$2\frac{5}{8}$	$\frac{3}{4}$	$4\frac{3}{8}$	$2\frac{3}{4}$	$\frac{3}{4}$	$5\frac{3}{16}$	$2\frac{3}{4}$	$\frac{3}{4}$	$4\frac{7}{16}$	$2\frac{3}{4}$	$\frac{9}{16}$	$1\frac{1}{8}$	$\frac{11}{16}$	$\frac{13}{16}$	$\frac{1}{8}$
1 " $4\frac{1}{4}$ "	$\frac{5}{8}$	$3\frac{3}{4}$	$2\frac{3}{16}$	$\frac{11}{16}$	4	$2\frac{3}{8}$	$\frac{11}{16}$	4	$2\frac{1}{2}$	$\frac{11}{16}$	$4\frac{11}{16}$	$2\frac{1}{2}$	$\frac{11}{16}$	$4\frac{1}{16}$	$2\frac{1}{2}$	$\frac{1}{2}$	1	$\frac{3}{8}$	$\frac{3}{4}$	$\frac{1}{8}$
1 " $2\frac{5}{8}$ "	$\frac{9}{16}$	$3\frac{3}{8}$	2	$\frac{5}{8}$	$3\frac{9}{16}$	$2\frac{1}{8}$	$\frac{5}{8}$	$3\frac{9}{16}$	$2\frac{1}{4}$	$\frac{5}{8}$	$4\frac{1}{4}$	$2\frac{1}{4}$	$\frac{5}{8}$	$3\frac{5}{8}$	$2\frac{1}{4}$	$\frac{1}{2}$	$\frac{15}{16}$	$\frac{9}{16}$	$\frac{11}{16}$	$\frac{1}{8}$
1 " 1 "	$\frac{1}{2}$	3	$1\frac{3}{4}$	$\frac{9}{16}$	$3\frac{3}{16}$	$1\frac{7}{8}$	$\frac{9}{16}$	$3\frac{3}{16}$	2	$\frac{9}{16}$	$3\frac{3}{4}$	2	$\frac{9}{16}$	$3\frac{1}{4}$	2	$\frac{7}{16}$	$\frac{13}{16}$	$\frac{1}{2}$	$\frac{5}{8}$	$\frac{1}{8}$
0 " $11\frac{3}{8}$ "	$\frac{7}{16}$	$2\frac{5}{8}$	$1\frac{1}{2}$	$\frac{7}{16}$	$2\frac{3}{4}$	$1\frac{5}{8}$	$\frac{1}{2}$	$2\frac{3}{4}$	$1\frac{3}{4}$	$\frac{1}{2}$	$3\frac{5}{16}$	$1\frac{3}{4}$	$\frac{1}{2}$	$2\frac{7}{8}$	$1\frac{3}{4}$	$\frac{3}{8}$	$\frac{3}{4}$	$\frac{7}{16}$	$\frac{1}{2}$	$\frac{1}{8}$

NOTE.—Particular attention is directed to the following:
1. It is important that the above dimensions be strickly adhered to.
2. To insure the shackles all leading the same way over the windlass, it is necessary that there be an odd number of links in each length of cable.

TABLE IV.—MAXIMUM TOLERANCES IN OUTSIDE DIMENSIONS OF STUD LINK CHAIN CABLES, ABOVE AND BELOW THE STANDARD DIMENSIONS.

Size of Chain, in.	Common Links.	Enlarged Links, End Links and Shackles.	
	Length and Width, in.	Length, in.	Width, in.
$\frac{7}{16}$	$\pm\frac{1}{32}$	$+\frac{1}{16}, -\frac{1}{32}$	$\pm\frac{1}{32}$
$\frac{3}{4}$	$\pm\frac{1}{16}$	$+\frac{1}{8}, -\frac{1}{16}$	$\pm\frac{1}{16}$
1	$\pm\frac{3}{32}$	$+\frac{3}{16}, -\frac{3}{32}$	$\pm\frac{3}{32}$
$1\frac{1}{4}$	$\pm\frac{1}{8}$	$+\frac{1}{4}, -\frac{1}{8}$	$\pm\frac{1}{8}$
$1\frac{1}{2}$	$\pm\frac{5}{32}$	$+\frac{5}{16}, -\frac{5}{32}$	$\pm\frac{5}{32}$
$1\frac{3}{4}$	$\pm\frac{3}{16}$	$+\frac{3}{8}, -\frac{3}{16}$	$\pm\frac{3}{16}$
2	$\pm\frac{7}{32}$	$+\frac{7}{16}, -\frac{7}{32}$	$\pm\frac{7}{32}$
$2\frac{1}{4}$	$\pm\frac{1}{4}$	$+\frac{1}{2}, -\frac{1}{4}$	$\pm\frac{1}{4}$
$2\frac{1}{2}$	$\pm\frac{9}{32}$	$+\frac{9}{16}, -\frac{9}{32}$	$\pm\frac{9}{32}$
$2\frac{3}{4}$	$\pm\frac{5}{16}$	$+\frac{5}{8}, -\frac{5}{16}$	$\pm\frac{5}{16}$
3	$\pm\frac{11}{32}$	$+\frac{11}{16}, -\frac{11}{32}$	$\pm\frac{11}{32}$
$3\frac{1}{2}$	$\pm\frac{3}{8}$	$+\frac{3}{4}, -\frac{3}{8}$	$\pm\frac{3}{8}$
4	$\pm\frac{3}{8}$	$+\frac{3}{4}, -\frac{3}{8}$	$\pm\frac{3}{8}$

DISCUSSION.

Mr. Merrill.

MR. W. L. MERRILL *(presented in written form)*.—Mr. Cox's very interesting paper describes briefly the work done by the General Electric Co. to produce cast steel anchor chain and quotes some of the results obtained from tests made upon the steel both annealed and quenched-and-tempered. Similarly the work of The National Malleable Castings Co. is described and results are given of tests made on the Naco chain. Direct comparison of the two products is not made, hence a very interesting difference is not emphasized. This difference is the result of the method of attack of the problem by the two sets of experimenters.

The General Electric Co. assumed that wrought iron has been and still is a satisfactory material, and that it would find a more sympathetic interest in chain having some approximation to the qualities of wrought iron chain than in one whose physical characteristics are radically different from the commonly used material. Therefore, they set out to make a commercially practical composition of cast steel which, while it was easily cast into the necessary forms and sizes, would be soft and ductile. Softer or milder steels can be cast, but not quite so readily as the 0.30-per-cent carbon steel selected. The required degree of ductility in such a steel may readily be obtained by simple heat treatment. The result is a steel not especially high in strength, although far stronger than wrought iron (in fact, the yield point is equal to or slightly higher than the ultimate strength of wrought iron), but which has sufficient elongation and reduction of area to indicate a good degree of ductility. The results quoted by Mr. Cox show about as low ductility as any we obtained, while other tests gave reduction of area as high as 49 per cent, with 29 per cent elongation. The average of the tests made on a great many heats would be about 35 per cent reduction and 21 per cent elongation. This metal, then, is not radically different from wrought iron in its tensile properties, and the approach to the physical characteristics of wrought

Mr. Merrill. iron is the more satisfactory when one considers that it is cast steel whose grain refinement is the result simply of heat treatment. Chain made from such steel would be stronger than wrought iron chain; that is, under either a static load or impact, a higher stress would be required to deform it, while when tested to destruction, it would be deformed nearly, if not quite, as greatly as wrought iron chain when fracture finally occurred. The General Electric Co. felt they had offered a good answer to the problem set them, namely, a cast chain stronger than and equally as tough as the wrought chain universally used.

As Mr. Cox describes it, The National Malleable Castings Co. saw the resemblance between the problems of cast steel anchor chain and car coupler knuckles, and offered the materials for chain which they had found satisfactory for the knuckles. The physical properties of the Naco steel are not given in detail in the paper, but probably will be stated in the discussion of the paper by the representative of The National Malleable Castings Co. It will be sufficient for our purpose now to say that the test results given in the paper indicate a material of quite great strength, whose elastic limit approaches fairly close to the ultimate strength and which, while not actually brittle, does not possess a very high degree of ductility. Chain made from such material may only be deformed by stresses, either static or dynamic, very much higher than are required to deform wrought iron chain. In fact, in some of the tests, deformation of the Naco chain did not begin until the application of a stress which had caused a prohibitive degree of distortion of wrought iron links. Finally, the Naco chain failed with a small amount of deformation, sufficient to indicate that the material, though "short," is not completely brittle. The general conclusion that Naco chain fulfilled all of the requirements of a good anchor chain and was superior to welded wrought iron chain was fully justified.

Here, then, those having in hand the general question of a satisfactory substitute for wrought iron chain were offered two materials, both stronger than wrought iron, but one of which, while considerably stronger than the other, was also much less ductile. Naturally the tests made to determine the fitness of either or both materials for the purpose included shock tests, and Mr. Cox's paper brings out the difficulty of successfully

Mr. Merrill. carrying out shock tests from which valuable and definite conclusions may be drawn.

I wish to call attention to the shock test of the links in the M. C. B. machine. The data from these tests might apparently indicate that a chain which would resist a large number of blows when suspended vertically and show no appreciable distress, had inherently better shock resisting qualities than a more ductile chain which would, after a smaller number of similar blows, stretch and finally break. This may or may not be the proper conclusion. Let us assume that we have two pieces of chain, one made from a steel in which the elastic limit and the ultimate strength are practically the same, and the second made from steel whose elastic limit is somewhat lower than the ultimate strength. In the case of the first chain, let us assume that the sample receives three blows of the tup from 20 ft. and that no punishment is evidenced by the chain because each blow is not of sufficient force to stress the chain to its elastic limit but is just under this. In the case of the ductile chain under the same conditions, let us assume that the chain stretches $\frac{1}{4}$ in. for each blow, or $\frac{3}{4}$ in. for the three blows. It might appear from this test that the first chain was far better than the second. Let us assume, however, that the first sample receives one blow of the tup from 22 ft. and that this blow will break the chain short. One blow from this same height on the ductile chain will simply stretch it an amount very little in excess of $\frac{1}{4}$ in.

In other words, ductile material will stretch before it fails and "short" material will break short. These are the inherent characteristics of the material. Therefore, the results in the paper showing, on the basis of the shock test, that with commercial wrought chain valued at one, Navy Yard chain is 4, and cast steel chain is 13, may be misleading if applied to the materials as such and used as an indication of their relative shock-resisting qualities. I wish in no way to give the impression that I do not believe that the Naco chain is not superior to any anchor chain ever produced, but wish simply to bring out the fact that too broad conclusions must not be drawn from the shock tests whose results are recorded in the paper.

The usual way for engineers to make use of stronger material is to lighten sections, thereby increasing fiber stresses while keeping them in safe proportion to the elastic limit; but when the form and dimensions are fixed, the use of stronger material increases the safety of the structure by increasing the elastic limit in proportion to the expected fiber stresses. Mr. Cox has shown that weight per unit of length, and hence cross-section, of an anchor chain is fixed for a vessel of given proportions. Therefore, advantage may not be taken of the increased strength of cast steel to decrease the size of the links as compared with wrought iron chain for a given vessel. Cast steel chain must, therefore, be stronger than wrought iron chain, and the Naco steel is so much stronger than wrought iron that stresses sufficient to distort links made from the latter make no permanent impression on the Naco chain. In fact, it is probably the case that no impact stress great enough to cause failure of the Naco chain will ever occur in service; hence the shortness of Naco steel is not a disadvantage in anchor chain, while the stiffness of Naco chain is an enormous gain. **Mr. Merrill.**

Mr. Brooks. MR. C. K. BROOKS (*presented in written form*).—Several months ago, when The National Malleable Castings Co. was invited to participate in the experimental development of cast steel chain, the first problem which required attention was the working out of suitable foundry methods for producing chain links in sand molds, and uniting them into continuous lengths of chain. A number of entirely successful equipments for making the molds was the result, four of which are shown in Figs. 1 to 4, 5 to 8, 9 and 10, and 11 to 14, respectively.

Connecting up the links into chain was accomplished in either of two ways: (1) the continuous process, in which the entire chain is poured from one heat, into previously prepared and united molds, by filling one interlinked mold impression after another; and (2) the pre-cast link process, in which half the links comprising a complete length of chain are cast separately, shaken out, cleaned, inspected, and made ready for incorporation into the finished chain. Subsequently, these links are placed in mold cavities and coupled up into continuous chain by pouring metal into other molds containing impressions for similar links, interlinked with the pre-cast links. Any of the illustrated methods of making molds is equally applicable to the continuous process or the pre-cast link process of making chain.

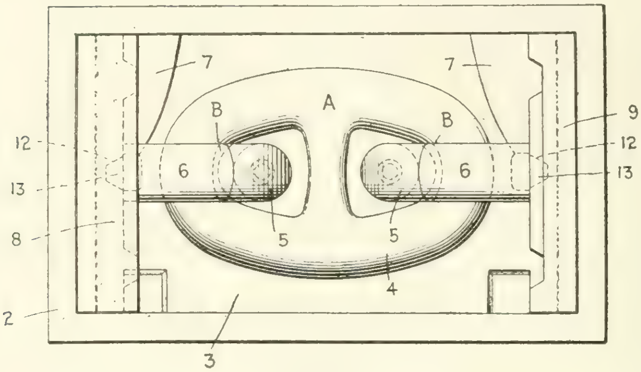


FIG. 1.

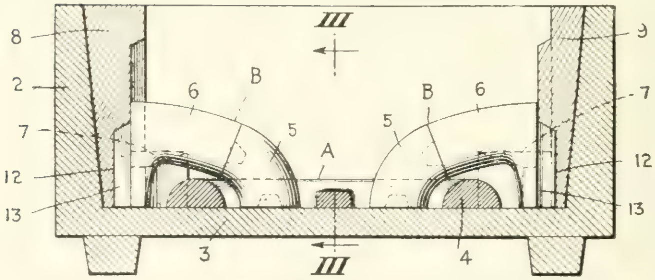


FIG. 2.

ILLUSTRATING FIRST METHOD OF MAKING MOLDS.

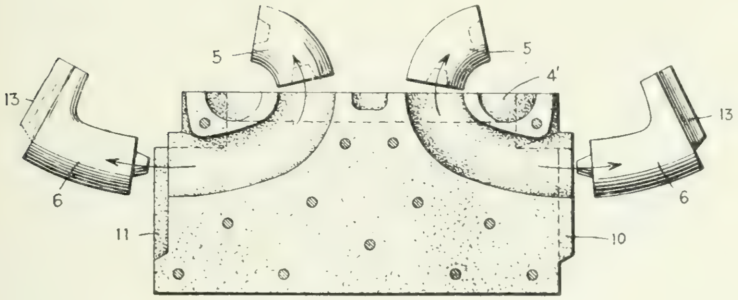


FIG. 3.

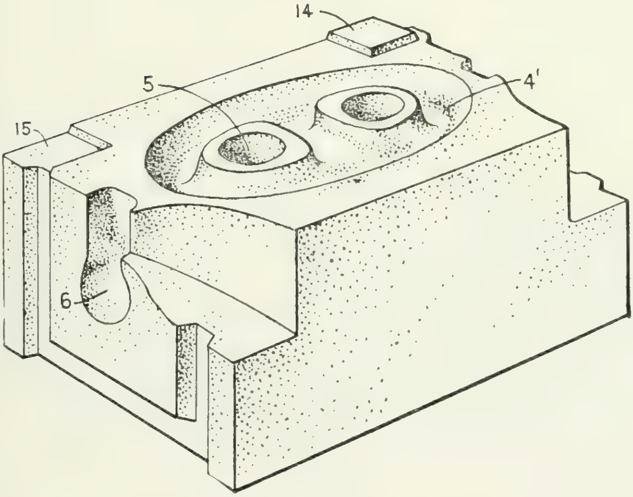


FIG. 4.

ILLUSTRATING FIRST METHOD OF MAKING MOLDS.

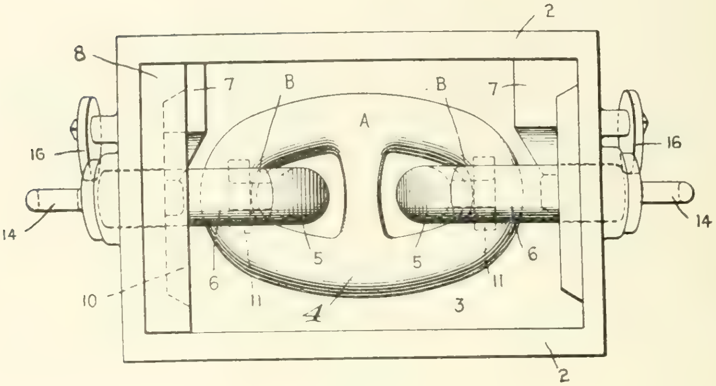


FIG. 5.

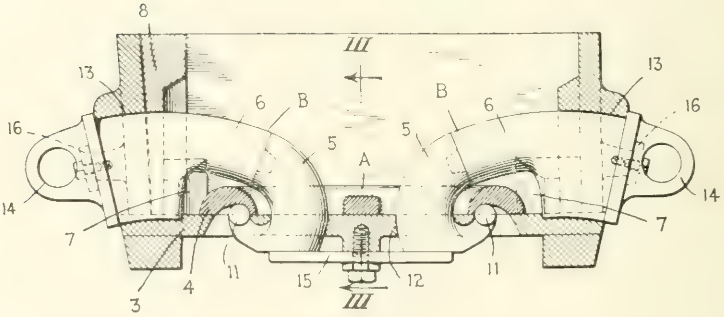


FIG. 6.

ILLUSTRATING SECOND METHOD OF MAKING MOLDS.

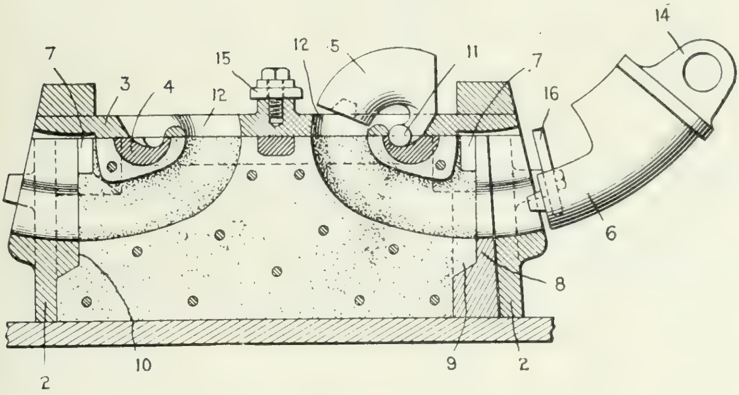


FIG. 7.

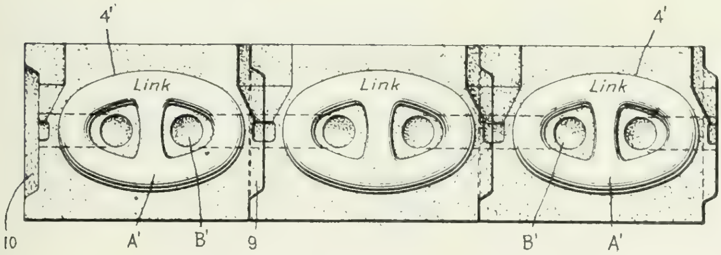


FIG. 8.

ILLUSTRATING SECOND METHOD OF MAKING MOLDS.

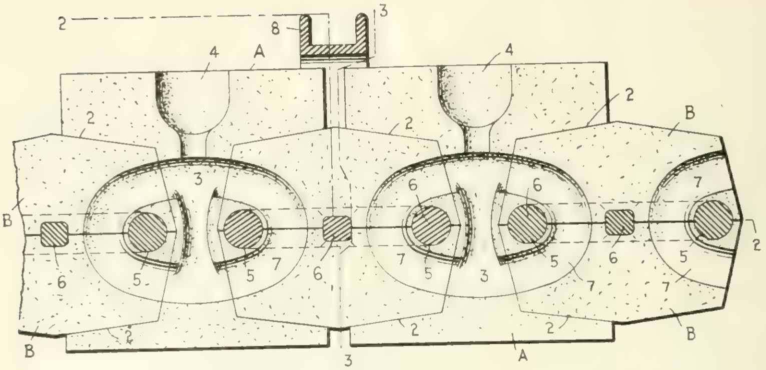


FIG. 9.

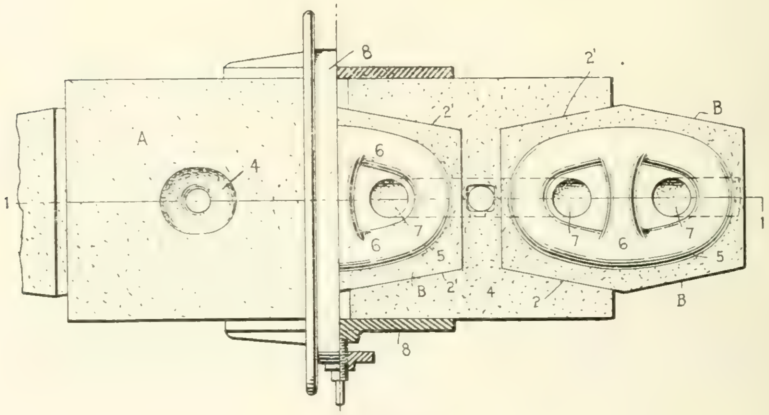


FIG. 10.

ILLUSTRATING THIRD METHOD OF MAKING MOLDS.

Mr. Brooks.

Another part of the foundry problem was the character of the mold. Recognizing the vital importance of sound castings in a product of this character, we came to the conclusion quite early in our experiments that all of the links should be produced in dry sand molds. The methods of application of gates and risers have also required some study, the details of which need hardly be set forth here. Suffice it to say that we have been able to secure very excellent results both in pouring through the stud and through the side of the link.

The character of the metal used by us in these experiments, and its handling in the heat treatment, have been touched upon in the paper by Mr. Cox. In our preparations for manufacture, the adaptation of the method of heat treatment used for our car coupler knuckles to ninety foot shots of chain has involved some problems, but these have been solved and the process will be practically identical in method and results.

Referring now to the results of physical tests on cast steel stud chain of our Naco steel, we felt that the testing facilities at our Sharon, Pa., steel castings plant, used principally in the manufacture of car couplers, were very well suited for the carrying out of the further tests which seemed desirable after the last experiments at Schenectady. Our suggestion having been accepted, we made plans to have ready as many different sizes of cast chain as possible in the short time available, and succeeded in preparing short lengths of $1\frac{3}{8}$, 2, $2\frac{1}{4}$ and $2\frac{7}{8}$-in. Naco cast steel chain, ready for test on March 1 and 2, 1918, at our Sharon plant.

The tests were conducted on a vertical screw type static testing machine of 1,000,000-lb. capacity and a standard Master Car Builders' drop testing machine. The chains subjected to static tension tests were supported by coupling each end link of the test chain to the cross head of the static testing machine by means of a testing shackle and pin as shown in Fig. 15.

Test chains consisting of five common stud or "A" links were subjected to a light load sufficient to reduce high bearing spots between adjacent links, which was then released and a measurement over the three middle links laid off. The elongation over this measurement was then taken at loads corresponding to the proof load, the breaking load, and the breaking load plus

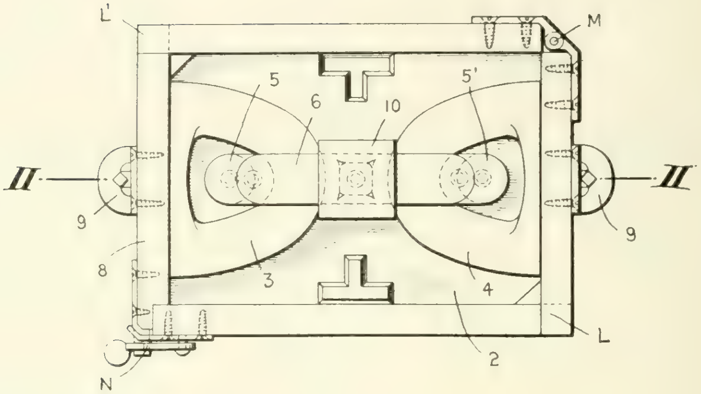


FIG. 11.

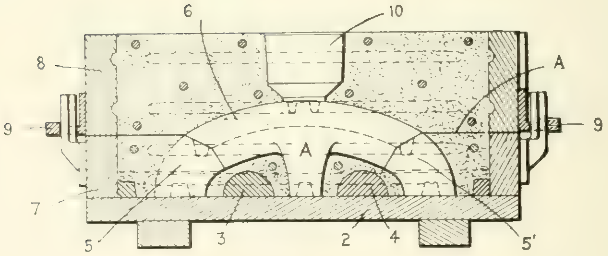


FIG. 12.

ILLUSTRATING FOURTH METHOD OF MAKING MOLDS.

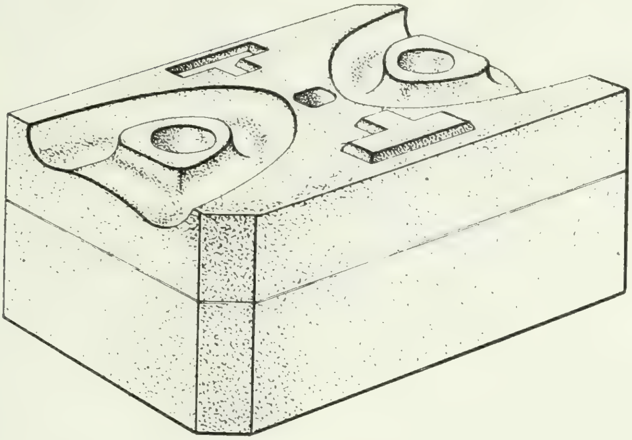


FIG. 13.

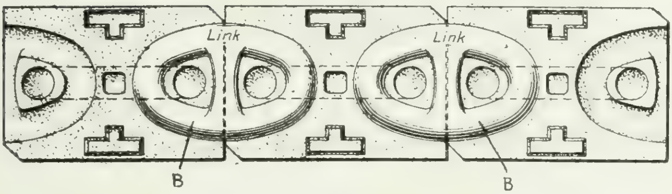


FIG. 14.

ILLUSTRATING FOURTH METHOD OF MAKING MOLDS.

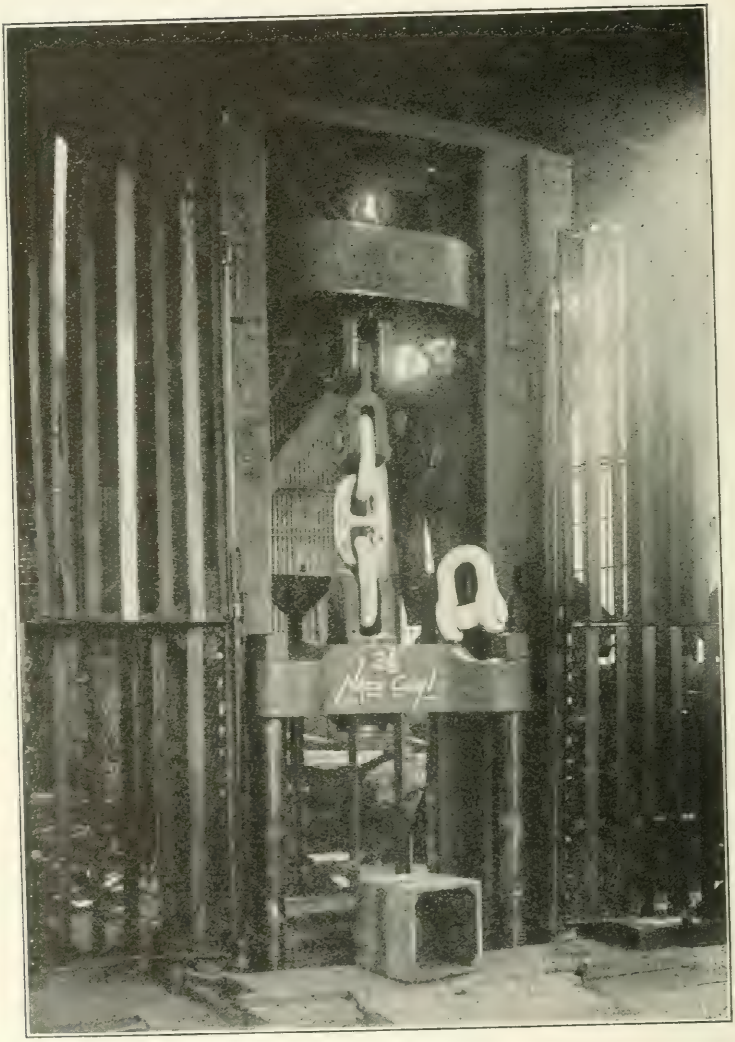


FIG. 15.—Static Tension Testing Machine.

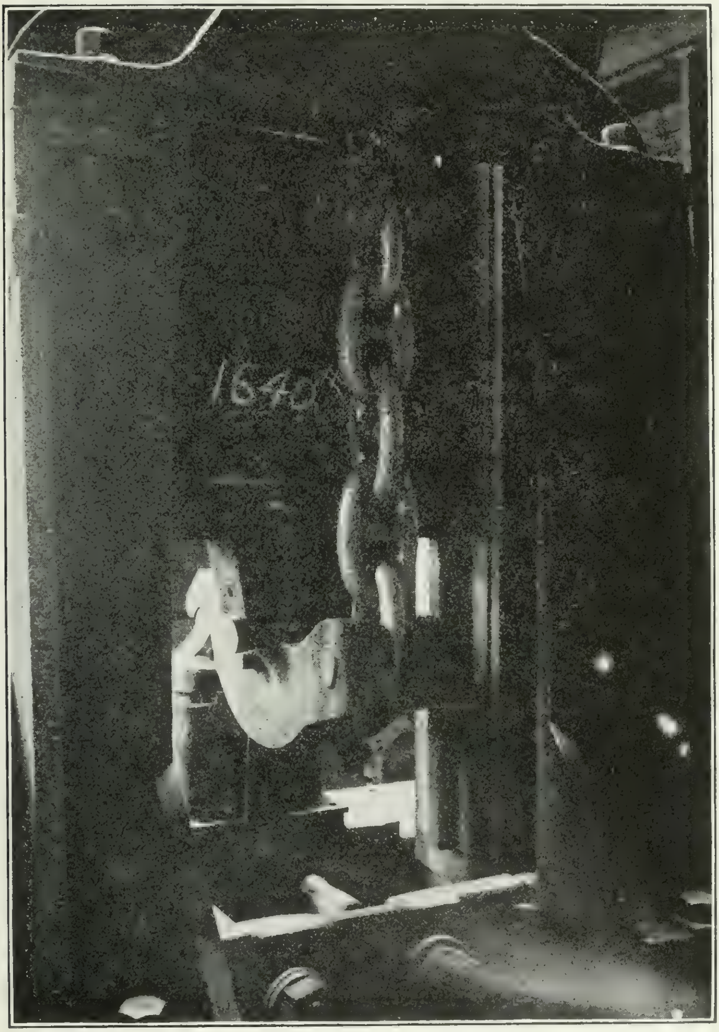


Fig. 16.—Dynamic Tension Testing Machine (M. C. B. Drop)—Tup Down.

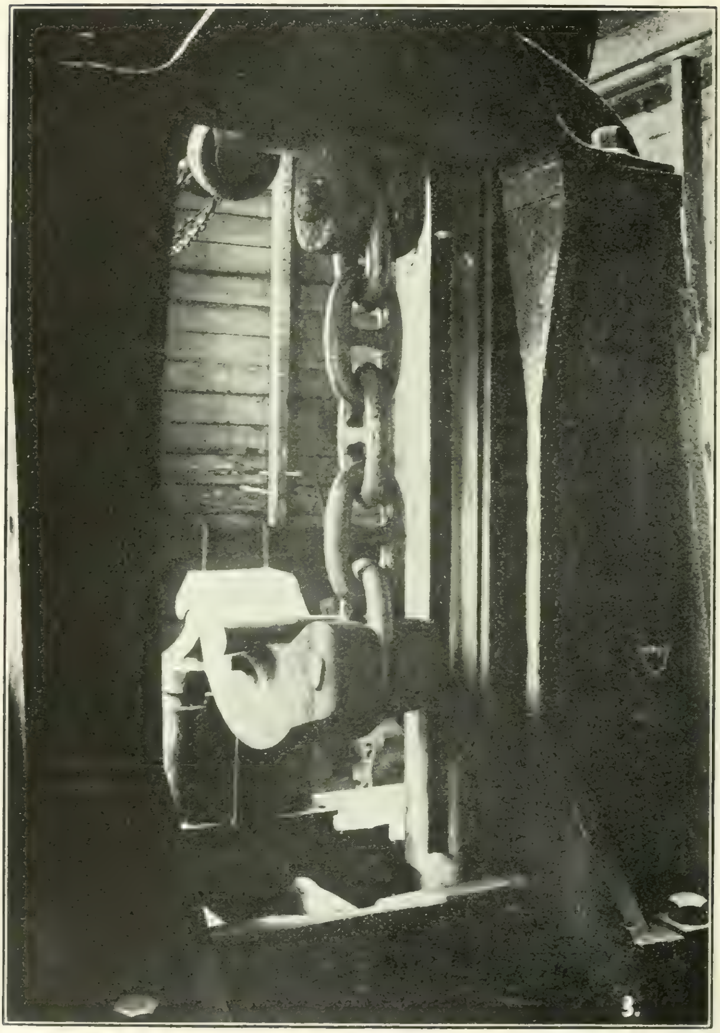


FIG. 17.—Dynamic Tension Testing Machine (M. C. B. Drop)—Tup Raised.

Mr. Brooks. 40 per cent, as specified by the Ship Classification Societies for the corresponding sizes of wrought chain. After these three

TABLE I.—STATIC TENSION TESTS OF "NACO" STEEL CHAIN.

Test No.	Size, in.	Weight of Test Chain, lb.	Elongation, in., after:			Load at Rupture, lb.	Remarks.
			Proof Load.	Breaking Load.	Breaking Load plus 40 per cent.		
1	$1\frac{3}{8}$	40	0.03	0.04	0.08	213 600	Broke No. 3 link. Section of metal solid.
2	$1\frac{3}{8}$	40	0.03	0.04	0.07	198 700	Broke No. 3 link. Section of metal few small blow holes.
3	$1\frac{3}{8}$	40	0.02	0.04	0.09	180 700	Broke No. 3 link. Section of metal honey-combed.
4		123	0.03	0.06	0.13	456 400	Broke No. 4 link. Small shrinkage in each fracture.
5	2	122	0.03	0.06	0.09	400 000	Broke No. 3 link. Section shows solid.
6	2	122	0.03	0.05	0.10	403 000	Broke No. 4 link. Section shows solid.
7	2	225	0.20	0.27	0.45	381 900	Broke top "E" link. Section shows few small blow holes.
8	2	223	0.10	0.22	0.63	346 500	Broke bottom "E" link. Section shows few small blow holes.
9	2	223	0.07	0.14	Not obtained	316 100	Broke bottom "E" link. Section shows few small blow holes.
10	$2\frac{1}{4}$	174	0.05	0.09	0.20	494 400	Broke No. 1 link. Section shows solid.
11	$2\frac{1}{4}$	174	0.07	0.13	0.33	495 400	Broke No. 3 link. Section shows solid.
12	$2\frac{1}{4}$	175	0.06	0.11	0.22	513 200	Broke No. 5 link. Section shows solid.
13	$2\frac{1}{4}$	172	0.02	0.05	0.14	502 400	Broke No. 3 link. Fractured through defect.
14	$2\frac{1}{4}$	171	0.03	0.07	0.16	491 900	Broke No. 5 link. No. 3 link defective.
15	2	...	0.65	0.65	0.67	452 700	Broke No. 2 link. Section shows solid. See also dynamic test No. 4.
16	$2\frac{7}{8}$	251	0.00	0.00	0.00	764 700	Broke "E" link. Section shows few blow holes in one side.
17	2	...	0.72	0.73	0.74	467 400	Broke No. 3 link. Section shows small shrinkage one side. See also dynamic test No. 8.

loads had been applied, released, and elongation measured, a load to destruction was then applied.

Test chains consisting of two sections of "A," "B" and "E" links coupled with shackle "D" were tested in the same

Mr. Brooks. manner, except that the elongation measurement was taken over the two "B" links. The $2\frac{7}{8}$-in. chain consisted of one each of the "A," "B" and "E" links and the elongation was measured on the "B" link only.

The test chains used in the drop testing machine were all of the 2-in. size and consisted of five stud or "A" links each. These chains were installed in the testing machine by connecting the upper link in a shackle bar and the lower link in an equalizer shackle by means of shackle pins passing through the eye of each link. This arrangement, which is shown in Figs. 16 and 17, is such that a part of the energy of the falling weight is transmitted to the test chain as a dynamic tensile stress. The over-all measurement of the middle three links of these test chains was laid off as in the static tests and the elongation measured after

TABLE II.—DYNAMIC TENSION TESTS OF CHAIN.

Test No.	Size, in.	Material.	Elongation, in., after 3 Blows at					Total Blows at 25 ft.	Total Blows at 30 ft.	Total Blows at 35 ft.	Chain Broke on	Total Elongation, in.	Remarks.
			5 ft.	10 ft.	15 ft.	20 ft.	25 ft.						
1	2	Wrought	0.02	0.05	0.15	....	....	..	..	..	1st at 20 ft.	0.15	Broke Nos. 4 and 5 links.
2	2	Wrought	0.00	0.02	...	....	....	..	..	..	2d at 15 ft.	0.02	Broke No. 1 link.
3	2	Wrought	0.00	0.02	....	....	....	..	..	..	2d at 15 ft.	0.02	Broke No. 1 link.
4	2	Naco.....	0.01	0.05	0.09	0.13	0.27	50	20	..	None	0.65	Chain installed in static Machine. See static test No. 15.
5	2	U. S. Navy	0.10	0.34	0.68	1.37	2.21	6	..	..	6th at 25 ft.	....	Broke No. 1 link through weld.
6	2	U. S. Navy	0.06	0.32	0.74	1.32	2.08	10	2	..	None	3.85	Surface fractures in all links. Chain installed in static machine and broke No. 2 link at about 241,000 lb.
7	2	Naco.....	0.02	0.02	0.03	0.05	0.10	10	1	..	1st at 30 ft.	0.24	Broke No. 4 link. Section shows solid.
8	2	Naco.....	0.08	0.10	0.15	0.19	0.26	10	10	10	None	0.72	Chain installed in static machine. See static test No. 17.

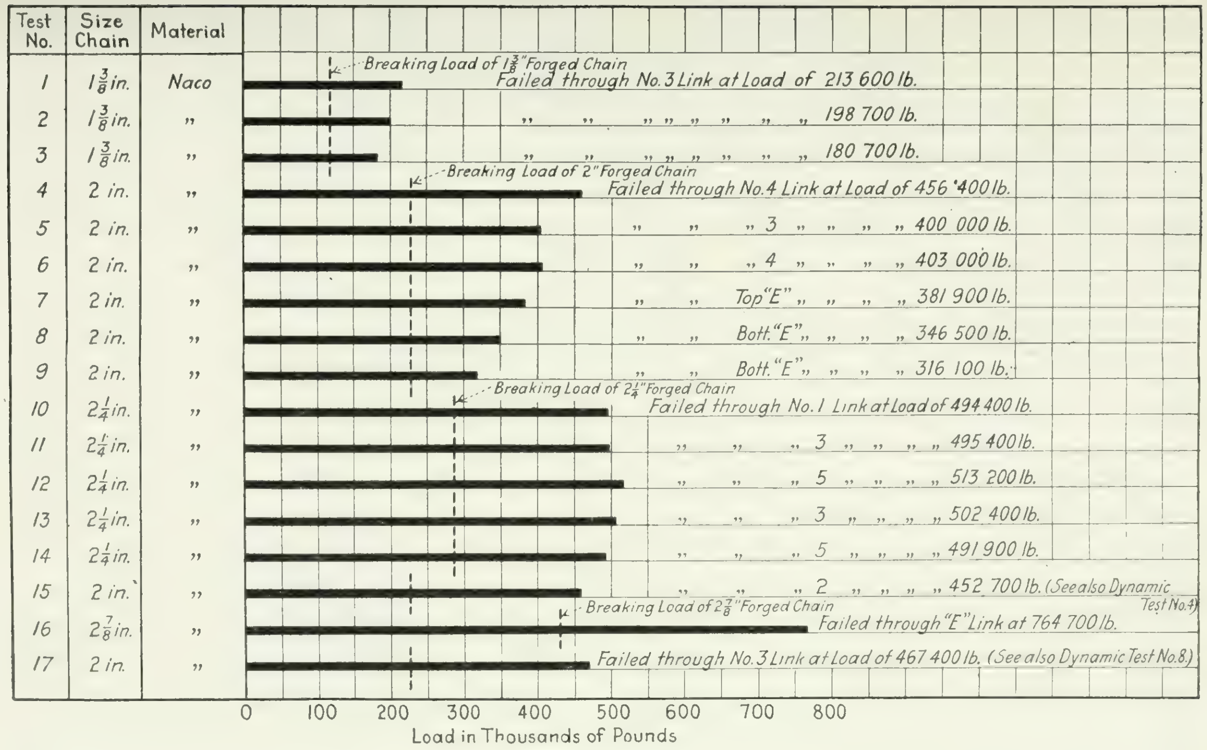


FIG. 18 —Static Tension Tests; see Table I.

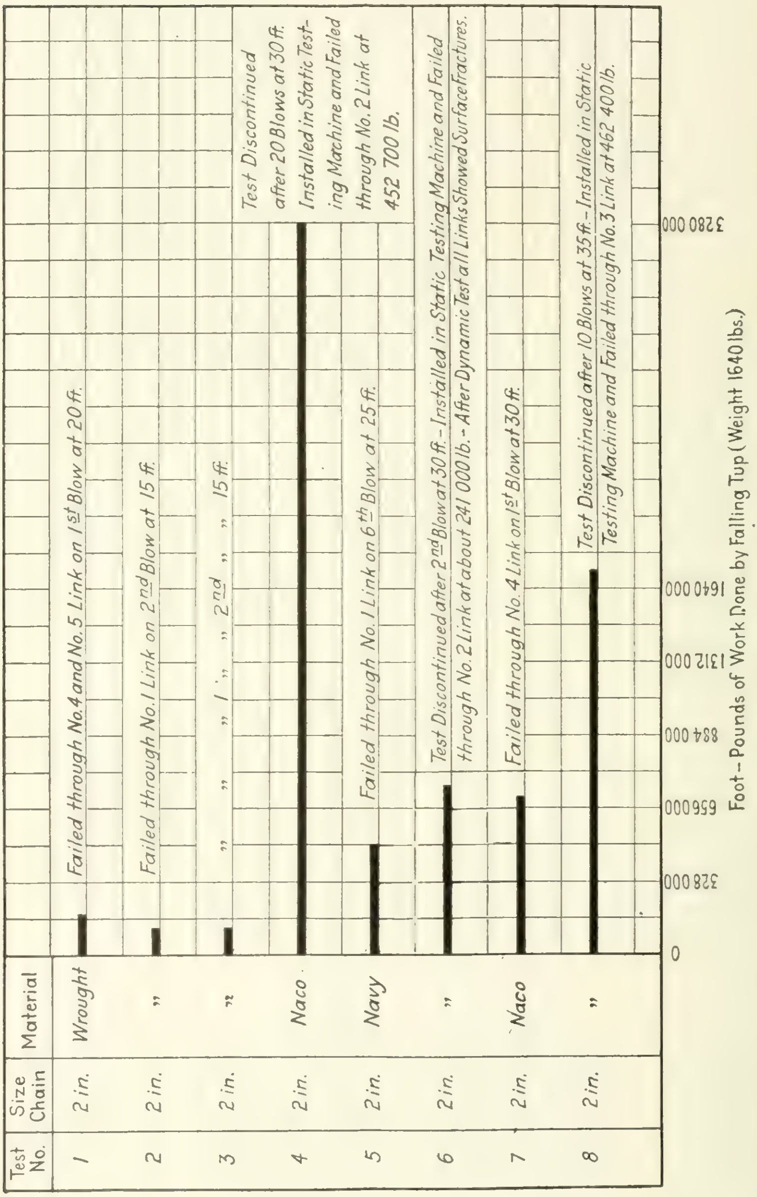


FIG. 19.—Dynamic Tension Tests; see Table II.

Mr. Brooks. the third blow from each of the specified heights. The weight of the tup was 1640 lb. and this weight was allowed to rest upon the equalizer when readings were laid out and elongation measured. In all these tests the numbering of the links was upward, commencing with the bottom link as No. 1.

Table I shows the results of all the static tension tests and Table II the results of the dynamic tension tests. Included among the dynamic tests are not only the tests of 2-in. Naco steel chain, but also certain tests on the same size specimens of commercial wrought iron chain, and samples from the Boston Navy Yard. Figs. 18 and 19 are graphic charts of the results tabulated in Tables I and II, respectively. Figs. 20 to 27, inclusive, are photographic reproductions of the various chains used in the foregoing tests.

The following detail tests are of especial interest:

DYNAMIC TESTS.

Dynamic Test No. 4: 2-in. Naco Steel Chain.—This chain was subjected to

3 blows at 5 ft.
3 " " 10 ft.
3 " " 15 ft.
3 " " 20 ft.
50 " " 25 ft.
20 " " 30 ft.

The chain showed no signs of failure whatever after this severe treatment, and the elongation over the links measured 0.65 in. This chain was then transferred from the drop to the static machine and subjected to the proof load, breaking load and breaking load plus 40 per cent, after which the load was increased to 452,700 lb., when the No. 2 link broke, showing solid sections at the fracture.

Dynamic Test No. 8: 2-in. Naco Steel Chain.—This chain was subjected to

3 blows at 5 ft.
3 " " 10 ft.
3 " " 15 ft.
3 " " 20 ft.
10 " " 25 ft.
10 " " 30 ft.
10 " " 35 ft.

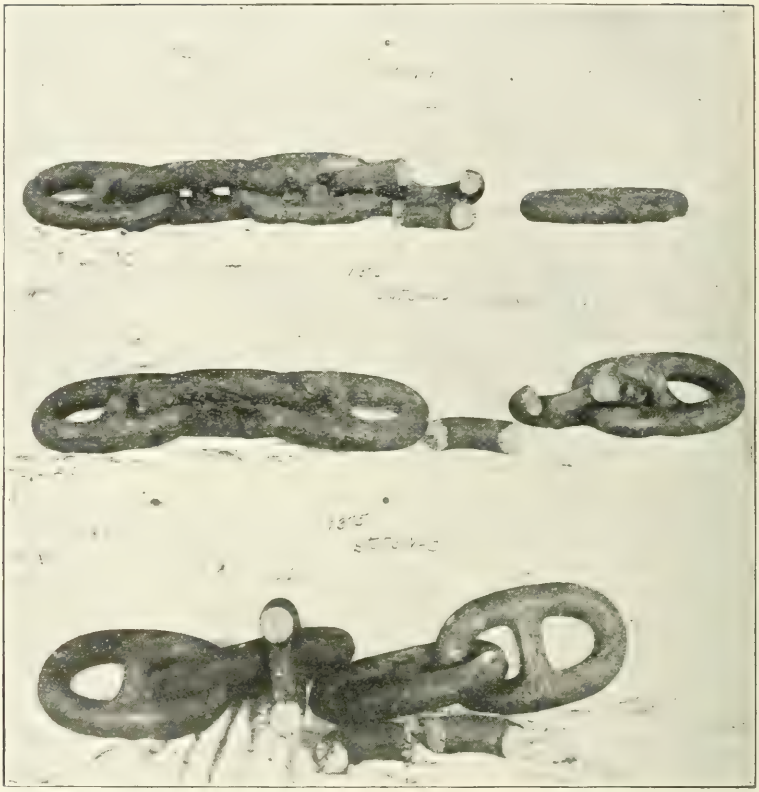


FIG. 20.—Broken Naco Chain, Static Tests Nos. 1, 2 and 3.

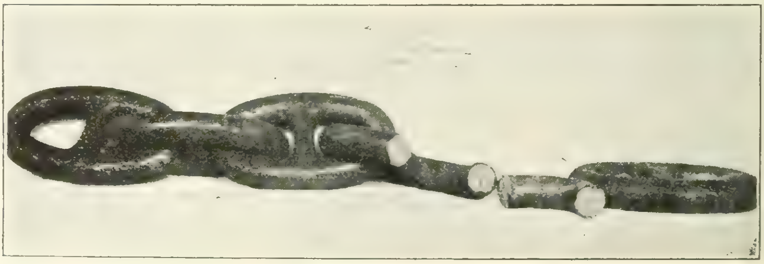


FIG. 21.—Broken Naco Chain, Static Test No. 15.

Mr. Brooks.

The elongation over three links was 0.72 in. with no signs of fracture, after which the chain was submitted to the same static loads as test No. 4 and broke through No. 3 link at 467,400 lb., showing solid metal at the fracture but with a small shrink at one side.

Dynamic Test No. 6: 2-in. Navy Chain.—This chain was subjected to

3 blows at 5 ft.
3 " " 10 ft.
3 " " 15 ft.
3 " " 20 ft.
10 " " 25 ft.
2 " " 30 ft.

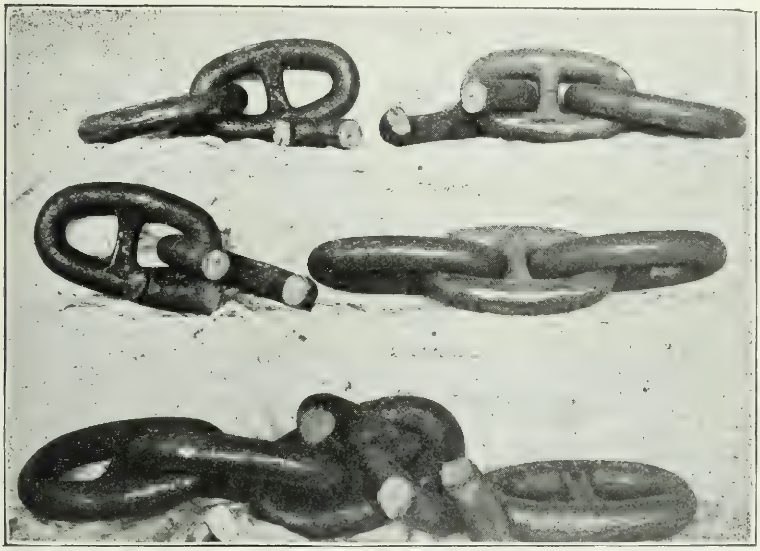


FIG. 22.—Broken Naco Chain, Static Tests Nos. 4, 5 and 6.

The test was discontinued at this point because of excessive elongation in the chain, which permitted the equalizer to interfere with its support and made it impossible to deliver the full blow to the chain. The elongation over three links was 3.85 in. and each of the five links was slightly fractured in one or more places. After the third blow at 20 ft. the elongation over three

Mr. Brooks. links was 1.32 in. and after the third blow at 25 ft. it was 2.08 in. Undoubtedly this chain was out of commission on account of distortion so far as serviceability is concerned after the third blow at 25 ft.

STATIC TESTS.

Static Tests Nos. 13 and 14: $2\frac{1}{4}$-in. Naco Chain.—These tests were made upon test specimens having serious shrinkages on one side of the No. 3 link opposite the stud, for the purpose of determining the effect of these defects. In test No. 13 the defective link broke through the defect at 502,400 lb. and in test No. 14 the No. 5 link broke at 491,900 lb., showing solid sections at the fracture. The second chain was retested, finally

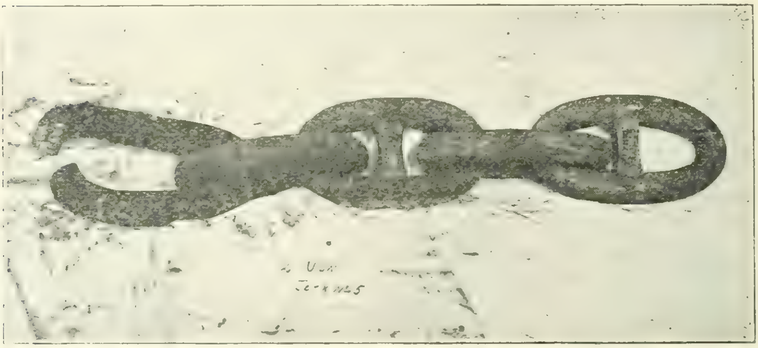


FIG. 23.—Broken Navy Chain, Dynamic Test No. 5.

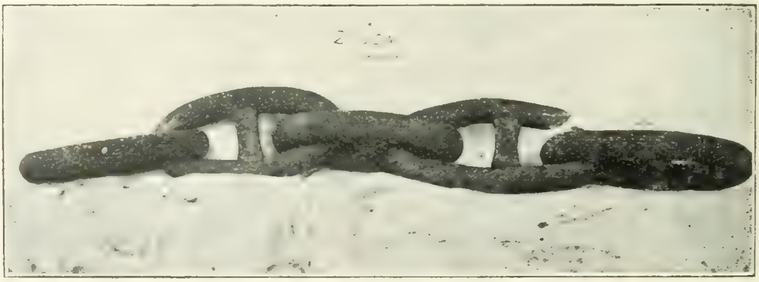


FIG. 24.—Broken Navy Chain, Dynamic Test No. 6.

breaking through the defect in No. 3 link at 502,200 lb. While neither of the above chains would have been considered suitable for commercial purposes and the defects would have been readily detected on a casual inspection, it is quite interesting to note the slight effect of the imperfections. **Mr. Brooks.**

Before bringing this paper to a close we feel that some reference should be made to our experience in the railway car coupler field during the past twenty years, for the reason that that experience has made possible the accomplishment of results in the cast steel chain problem in a few weeks which otherwise would have taken several years to attain.

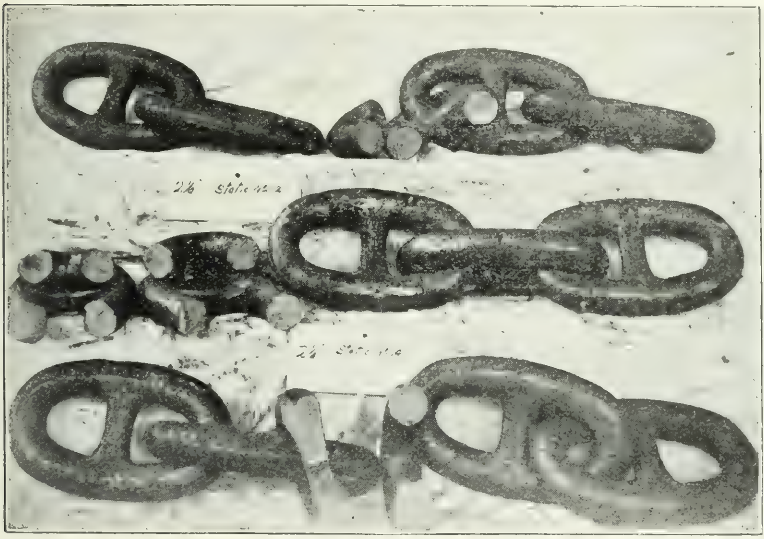


FIG. 25.—Broken Naco Chain, Static Tests Nos. 11, 12 and 14.

As you are probably aware, the knuckle of the Master Car Builders' vertical plane type of coupler has involved a very serious and difficult problem, particularly in the past ten years. Since the adoption of the Standard Master Car Builders' contour for that coupler in the early 90's,—a standard which, because of the requirements of interchangeability, has remained substantially without change up to the present time,—there have been enormous increases in locomotive tractive effort, size and

Mr. Brooks. weight of car equipment, and tonnage hauled per train. The limitations of the M. C. B. contour, formed partly by the coupler head, and partly by the knuckle, have imposed certain fixed dimensions upon the size of the hub of the knuckle—its weakest point—which have effectually barred any substantial increase in section. The stress to which this hub section is subjected is really enormous, for the knuckle, which is in the form of a hook pivoted at its middle, transmits not only the entire tractive effort of the locomotive in pulling the train, but also receives shocks of great suddenness and intensity, both jerks and buffs, due to the surging of trains, the running out and in of "slack" during application and release of brakes, and in coupling by impact. Dynamometer car records have shown time and again that these pulls and buffs are frequently many times in excess of the tractive effort of the largest modern locomotives.

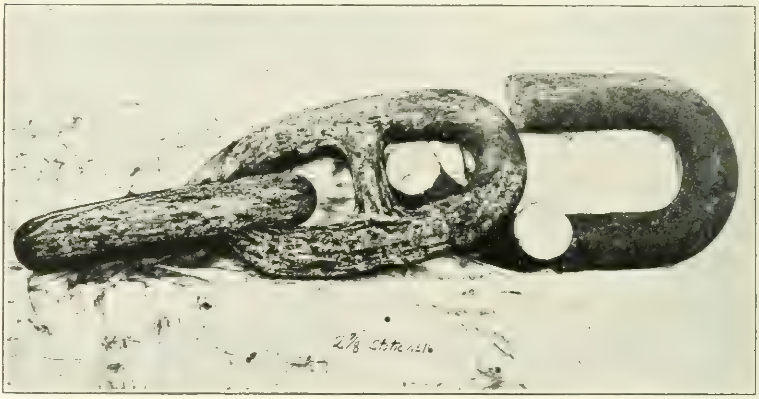


FIG. 26.—Broken Naco Chain, Static Test No. 16.

From the locomotive pilot to the caboose there is no other part of the railroad equipment subjected to more severe or frequent shock than the knuckle; no part which it is more essential to maintain as nearly as possible in its original form without distortion; and no part more strictly surrounded by conditions which limit possible changes of design for increasing its strength.

Notwithstanding the evil effects of knuckle distortion upon proper maintenance of contour, it has been felt for years that **Mr. Brooks.** nothing but a material with high ductility would be capable of receiving these severe shock stresses. Part of the basis for this feeling has been the theory that a very ductile material would, by its elongation, absorb some of the shock and so save itself from rupture; but the difficulty with this is that *the major part of this elongation is available only after the elastic limit of the material has been passed.*

Two possible solutions for this problem have presented themselves: first, the use of a special material with very much higher capacity to resist both static and dynamic stresses, and second, the adoption of an entirely new and heavier coupler with modified contour, having sufficient sectional areas to make resort to special materials unnecessary. The latter method was followed by joint action of all the coupler manufacturers, under the initiative and jurisdiction of the Master Car Builders' Association of the railroads, and to-day, after six or seven years' development, we have one standard coupler, somewhat heavier and very much stronger and with its knuckle able to

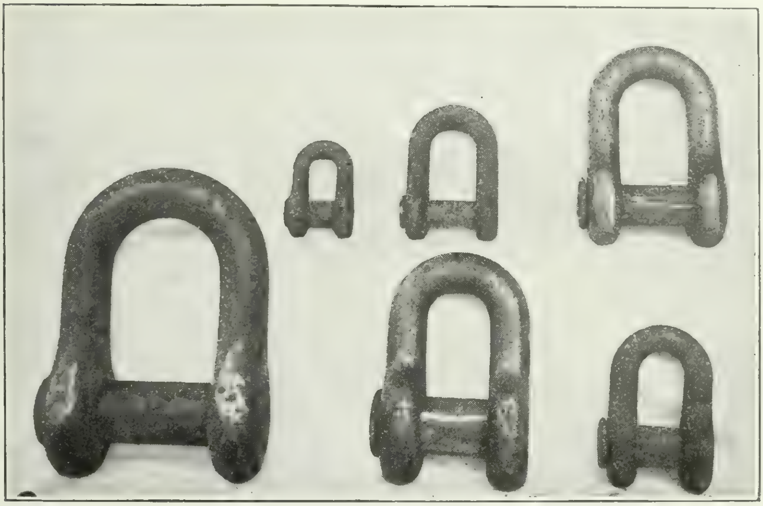


FIG. 27.—Shackles and Pins.

Mr. Brooks. meet the demands of service, though made of ordinary open-hearth steel.

In the meantime, realizing the importance of the problem, and the probable length of time involved in developing a standard coupler, we began an exhaustive search for a suitable special material to use in our knuckles. In the early days we started making couplers by the acid open-hearth process, later changing to basic, but our experience with both these steels led us to believe that there was no possibility of increasing the tensile strength sufficiently without loss of ability to withstand shock which would only result in failure to withstand the required M. C. B. drop tests, which tended to compel the use of a very soft material. We then began a series of experiments in the electric furnace with high-carbon steels heat-treated, and later with alloy steels. Marked improvements in tensile strength were the result, but the ability to withstand shock did not increase, and in many cases was diminished. Finally we arrived at a special material to which we later gave the name "Naco" steel, which combined with a high tensile strength a very extraordinary ability to withstand shock. This material, now used in our coupler knuckles, has raised their elastic limit more than 225 per cent, and their ability to resist shock stresses nearly 100 per cent over ordinary open-hearth steel. The amount of shock which these Naco knuckles will take without breakage or serious distortion is beyond anything in our experience, and we have been able to develop a specification of our own, along the lines of M. C. B. coupler specifications, but calling for only half the amount of knuckle distortion with the same amount of shock in the drop test—a feature of the greatest advantage in the maintenance of proper contour in service.

Our inspection department is using this M. C. B. drop testing machine daily in the acceptance or rejection of our Naco steel knuckle heats, and make on the average of 3000 tests per year. The performance in this machine is incontestably borne out in service by the record of more than a million Naco knuckles in use without a report from any railroad or from our road service department, of a single failure of a Naco knuckle since the experimental period was passed.

There are so many points of resemblance between the coupler-knuckle problem and that of cast steel chain as we understand it, that we were able to start at a point which otherwise must have taken years of study and development, with the results set forth. In our opinion, a proper specification for cast steel chain would require the making of links in dry sand molds or cores, but other details of manufacture should be left optional with the manufacturer. For the chemical requirements, the steel should be made by the electric furnace process, with phosphorus and sulfur limits of not over 0.04 per cent. The physical requirements should be sufficiently rigid to insure sound material, and should embody a dynamic test sufficiently severe to put the ability of the steel to withstand shock beyond any question of doubt. For this latter purpose we believe the standard M. C. B. drop testing machine presents the most readily available commercial machine, and a shock test on short pieces of test chain similar to the tests carried out at our Sharon plant seems to be as closely representative of the service to which anchor chain is subjected as any laboratory test can be. **Mr. Brooks.**

MR. H. D. VAN DOORN.—It was my privilege to witness most of the tests on cast steel anchor chain and the feature which is of the greatest interest to the manufacturers of anchor windlasses is the uniformity of all links and the lack of elongation. **Mr. Van Doorn.**

In the past it has been necessary for the windlass maker to obtain the dimensions or a sample of the chain which was to be used on each windlass so that the wildcats, or chain wheels, could be fitted to properly handle that particular chain. This condition existed before the war, when orders were received for only one or two windlasses at a time.

Since the war, however, orders have been placed for windlasses in lots of 100 to 150, and in order to obviate the necessity for individual samples the American Bureau of Shipping, in cooperation with the chain makers and windlass makers, developed a new set of chain dimensions and established minimum and maximum tolerances and all chains must now be made within these tolerances. This is a great improvement, but it is still somewhat difficult to fit a wildcat so that both the minimum and maximum length of links will work satisfactorily.

In order to make a chain run over a wildcat it is necessary to so fit the wildcat that when the short links pass over it they

Mr. Van Doorn. will rest on the center at the base of the lugs, while the long links will ride up on the lugs and will not rest on the center. Thus it will readily be seen that if three or four long links come together and too much variation is allowed, they will gradually climb up to the top of the lug and then slip over the lug entirely for a link or two until the chain catches a lug and settles into place again on the wildcat. This frequently happens in practice and the shock to the windlass and chain is tremendous.

The difficulty in fitting wildcats to links of varying dimensions will be realized by considering a $2\frac{1}{4}$-in. chain. The variations for this size are $\frac{1}{4}$ in. longer or $\frac{1}{4}$ in. shorter than the standard dimension, or a total of $\frac{1}{2}$ in. per link or 3 in. in six links, which is the customary number of links used in fitting up the wildcat.

It is therefore very desirable to make chain with as little variation as possible, and tests have demonstrated that there is practically no variation in the cast steel chain. If there was no variation the windlass maker could fit up the wildcat for a given size of chain to the standard dimensions and any chain of that size would work properly over that wildcat.

I was asked the other day how much a chain could elongate before it would become inoperative on a wildcat. I do not think any data have ever been obtained to throw light on this point; but I believe that a chain would not be operative if a majority of the links were any longer than the maximum tolerance allowed by the Bureau of Shipping. This entire matter, involving also the standardization of design of wildcats, is one which it seems to me might well be considered in a broad, cooperative way, as outlined in the papers presented at last evening's session on Cooperation in Industrial Research.

There is one other matter that should be made the subject of research, namely, the amount of friction caused by the anchor chain being drawn through the hawse pipe. For years nothing was known as to the amount of this friction, and windlass makers arbitrarily assumed it to be 100 per cent of the weight of the anchor and chain which was hanging outside of the hawse pipe. When electrically driven windlasses were first installed on navy vessels, one of the electric companies took some readings and determined that in that particular vessel the hawse pipe and deck friction amounted to only 20 per cent. Of course, the

Mr. Van Doorn. friction will vary with the angle of the hawse pipe and its shape at both ends, so that it probably would not be safe to assume 20 per cent as a standard simply because one test showed that amount.

In conclusion, I wish to express the hope that the cast steel chain will come into very common use, as a great deal of trouble with wildcats will thereby be avoided.

Mr. Lasier. MR. E. L. LASIER.—There are certain conditions, stresses and "tests" which anchor chain encounters in service which cannot readily be reproduced in the laboratory. I mention this because from the papers which have been presented and the discussions which have been offered it appears that reliance has been placed upon the results of shock and other tests as a guarantee of the service quality of the chain itself.

Let me give just one illustration of a condition met with in service, which cannot be readily reproduced in laboratory tests of chain. I mention this one illustration because if that is sound, the point which I have in mind is proved.

Chain cable in service is not subjected, in general, to a direct pull; usually it is a twist and a pull, or a pull and an impact on kinked chain or chain which has fouled against the keel or stem of a ship. The shock tests which have been and are under consideration by the Sub-Committee on Cast Steel Chain of Committee A-1 and which are superficially covered in Section 7 of the Tentative Specifications for Electric Cast Steel Anchor Chain[1] which have just been adopted as tentative, will give results upon the shock-resisting ability of the material of which the cast steel chain is made. Such shock tests, however, will not conclusively indicate the ability of the manufactured chain to resist the service stresses to which it is liable to be subjected. Furthermore, only experience in service will afford a reasonable guarantee of the homogeneity and uniformity of cast steel chain as well as yield data upon the wearing effects of rough surfaces on adjacent links.

Of course I note that the proof loads specified in Section 6 (*a*) of the specifications are unusually high; they are approximately equal to the required breaking loads for the same size chain specified in Navy Department specifications for wrought iron

---

[1] *Proceedings*, Am. Soc. Test. Mats., Vol. XVIII, Part I, p. 460 (1918).—ED.

Mr. Lasier. chain cable. This factor of safety—for such it is in fact—will, it is believed, form a satisfactory and safe working basis for the experimental development of cast steel anchor chain.

Because it is not believed, however, that direct impact tests in the laboratory, no matter how severe, exactly reproduce the conditions of twist and pull and impact to which chain is subjected in service, the Navy is obtaining six $2\frac{1}{4}$-in. cables, two of "Naco" steel, concerning which we have heard, two of electric-welded steel, and two of electric-welded wrought iron. Record will be kept of the processes of manufacture of these cables, the chemical, physical and mechanical characteristics of the material and of other data that may be available; such cables will be issued to naval ships and will then be subjected to severe service conditions. I believe that when the results of those service tests are obtained, we will be in a better position to talk about the satisfactoriness of cast steel anchor chain and definitely to draft specifications for that material or possibly to improve processes of manufacture.

These remarks should not be interpreted as an objection to cast steel chain, but rather as an encouragement of the development of that material. I merely desire to caution against the drawing of premature conclusions or the final drafting of specifications for cast steel chain.

Cast steel chain will undoubtedly, during the coming year, be used to a considerable extent in the merchant marine, and the results of such usage will be valuable in judging further the satisfactoriness of the material in question. In this connection it may be well to call attention to the fact that the navy service tests heretofore mentioned will be more severe than will the tests to which chain cable will be subjected in the merchant marine. In the navy, ships drop anchor more frequently and possibly heave in cable more quickly than in the merchant marine. Moreover, merchant ships almost invariably can drop anchor in sheltered harbors and in comparatively shallow waters while navy vessels may not be so fortunate.

I should like to ask the gentlemen who have conducted these tests two questions:

In the first place, has a uniformity of product been obtained in the manufacture of cast steel chain; that is, based on surface inspection, appearance of the fractures, etc., is there reason to believe that a homogeneous material is commercially obtainable, free from blowholes, scabs, shrink holes, honey combing, sponginess, and similar defects? If such is not the case it would appear that further development in the commercial manufacture of cast steel chain is necessary before a safe product can be obtained. **Mr. Lasier.**

In the second place, are there any comparative data upon the relative surface appearances of cast steel anchor chain and wrought iron chain of the same sizes? The presence of fins, sharp projections and uneven surfaces in chain will of course tend to cut through connected links and thus in time reduce the strength value of the cable. There is a difference between a "workmanlike" finish and a "smooth" finish.

MR. H. JASPER COX.—In reply to Mr. Lasier, I may say that even in the initial stages of the development of this chain the uniformity obtained has been most promising. Of course, a number of faulty links have been cast, some having considerable surface defects which would have immediately caused their rejection from a length of chain. As a matter of interest, to indicate the margin of safety in this chain, these defective links have been pulled and have shown a higher tensile strength than the statutory test for wrought iron chain. **Mr. Cox.**

I consider that the points raised in Mr. Lasier's second question are provided against by Section 4 of the specifications alluding to the "finish" required, and under this clause any fins, sharp projections or uneven surfaces which might be injurious or affect the strength of the chain, are required to be removed. My general impression from the cast steel chain which I have seen produced is, that it can be, and will be, not only more uniform in shape and size of link, but of better general finish than wrought iron chain.

In the early stages of this investigation it was suggested to try this chain out in actual service before approving of its general adoption, but you will readily understand such a procedure would have involved a delay of months, if not years. The matter was urgent, very urgent, and we had perforce to be guided instead by the tests described in this paper.

MR. BROOKS.—By way of explanation of the last point which Mr. Cox has just made, I might say that the principal **Mr. Brooks.**

Mr. Brooks. obstacle to producing full lengths of chain which confronted us during this development period, was the physical limitations of our heat-treating facilities. The short lengths of chain submitted for the experimental tests were readily handled in the car-coupler-knuckle heat-treating furnace at our Sharon plant, but the treating of 90-ft. shots require a specially constructed furnace which has made it impracticable to produce chains of such length up to the present time, although it will not be long now before we are equipped to do that.

TOPICAL DISCUSSION ON SEASON AND CORROSION CRACKING OF BRASS.

SEASON CRACKING AND SPLITTING OF CONDENSER TUBES AND PIPES.

By William Campbell.[1]

The literature on "Season Cracking" has been discussed by Merica and Woodward in their admirable paper on "The Failure of Brass, Microstructure and Initial Stresses in Wrought Brasses of the Type 60 per cent Copper and 40 per cent Zinc."[2] The chief cause of failure of brasses is initial internal stresses, the presence of which was first clearly set forth and the intensities actually measured by Heyn. In his paper on "Initial Strains in Cold-Wrought Metals and Some Troubles Caused thereby,"[3] he gives a remarkable example. A cold-drawn bar of composition, copper 57.8, zinc 40.8, lead 1.35 per cent, was examined for internal stresses soon after drawing and again after two years. A measurable change had taken place during this time. The metal was reheated to 160° C. for three hours which reduced the stresses to about half their original amount. Heating to 230° C. for three hours reduced them to a negligible quantity. This temperature is below that at which softening begins, or recrystallization normally makes its appearance, as shown by the work of Mathewson, Price, Davis and others.[4]

During the past three years a number of tubes and pipes have been examined with a view to determining the cause of failure by cracking and splitting. A superficial examination showed that there were two distinct types of failure: (1) the irregular cracking so characteristic in spun brass, brass pipe, cartridge cases, rods and bars, commonly called "season cracks," and (2) longitudinal cracks, perfectly straight, a few inches to several feet in length, found in condenser tubes of admiralty metal (copper 70, zinc 29, tin 1 per cent) after use in marine work for a very short time. In the former, where the metal had been subjected to the action of water or steam, more or less corrosion (dezincification) had occurred. In the latter such corrosion was generally, but not in all cases, absent.

---

[1] Professor of Metallurgy, School of Mines, Columbia University, and Metallurgist, New York Navy Yard.

[2] *Technological Paper No. 82*, Bureau of Standards, 1917.

[3] *Journal*, Institute of Metals, Vol. XII, pp. 3–37 (1914).

[4] Grard, *Revue de Metallurgie*, Vol. VI, 1069; Mathewson and Phillips, *Transactions*, Am. Inst. Min. Engrs., Vol. LIV, p. 608; Price and Davidson, *Proceedings*, Am. Inst. Metals, 1916; Davis, *Proceedings*, Am. Soc. Test. Mats., Vol. XVII, Part II, p. 167 (1917).

Under the microscope, the structure of the metal varied from extremely distorted grains on the one hand to grains of equiaxial shape, showing little distortion, on the other. Both good and bad material were found in each type of structure, showing that microstructure had little or no influence in the failures. The following micrographs illustrate the various types of structures met with during the examination of condenser tubes:

Fig. 1 shows the cross-section of one of the typical longitudinal cracks which had almost reached the inner surface. This crack is wide at the outer surface, as if this surface had been in tension. This photograph is typical of all of the longitudinal cracks. A variation from extremely fine to very coarse grain structure was shown by etching.

Figs. 2 to 5 show progressive variation from fine to coarse grain structure. All of these figures show little or no distortion of grain. In some cases the material is distinctly streaky near the surface, as shown in Figs. 6 and 7.

Many cases have been found in which the longitudinal cracks were irregular in cross-section. Fig. 8 is typical of such irregularity, which is apparently due to faulty material, the fault originating before the metal was drawn. Many tubes showing these radial cracks were found to be considerably hard drawn. Such material is shown in surface section and cross-section respectively in Figs. 9 and 10.

In many cases the grain size varies considerably in the same section. Fig. 11 is taken from a split section and the variation in grain size is very marked. The material shows cold working.

The condenser tubes which show typical season cracking

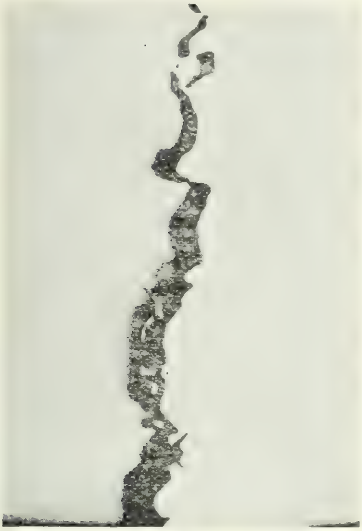


FIG. 1.—Cross-section of a Typical Longitudinal Crack. (× 75.)

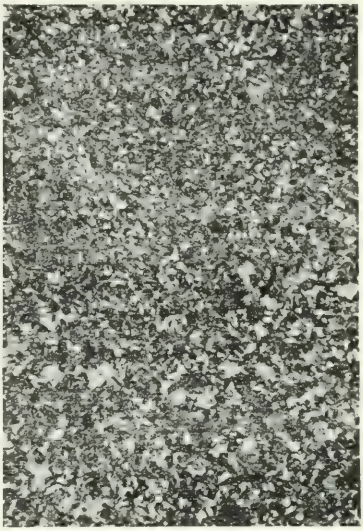


FIG. 2.—Typical Fine Grain Structure. (× 75.)

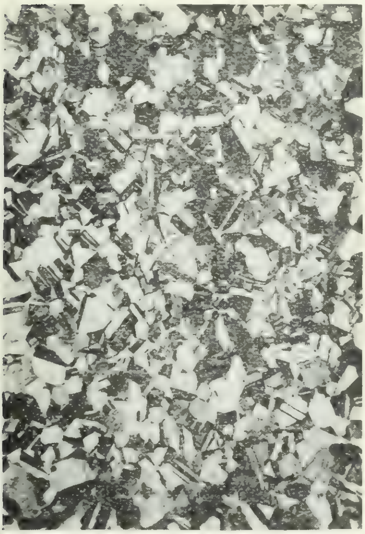


FIG. 3.—Intermediate Grain Structure. (× 75.)

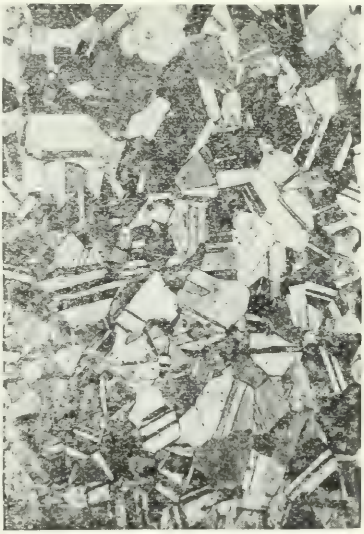


FIG. 4.—Medium-size Grain Structure. (× 75.)

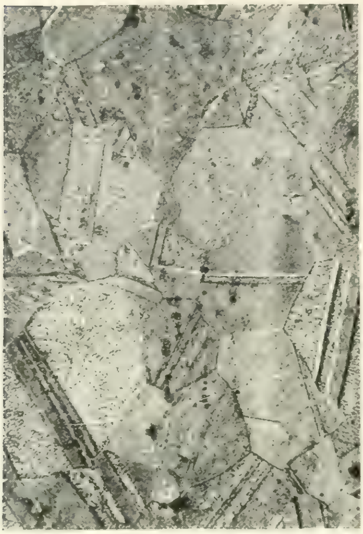


FIG. 5.—Coarse Grain Structure. (× 75.)

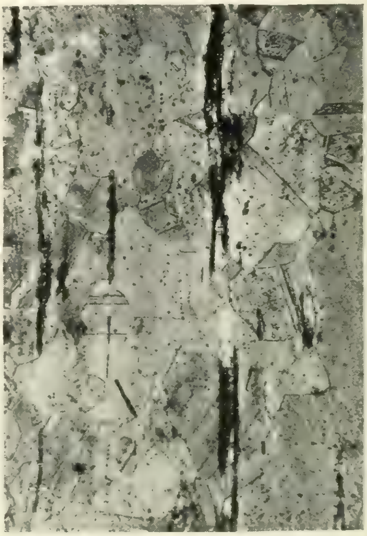


FIG. 6.—Longitudinal Section of a Streaky Tube. (× 75.)

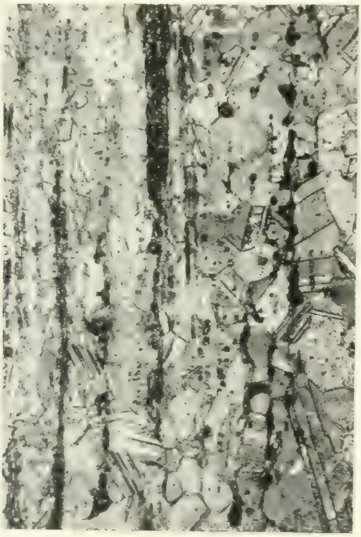


FIG. 7.—Markedly Streaky Longitudinal Surface Section of the Tube shown in Fig. 6. (× 75.)

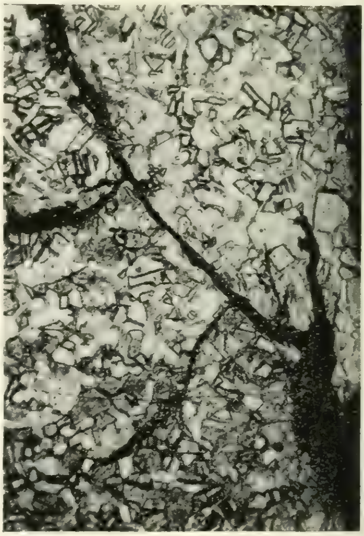


FIG. 8.—Typical Irregularity in Cross-section of Longitudinal Cracks. (× 75.)

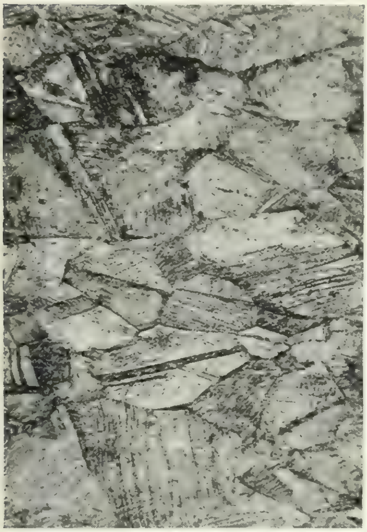


FIG. 9.—Hard Drawn Material, Surface Section. (× 75.)

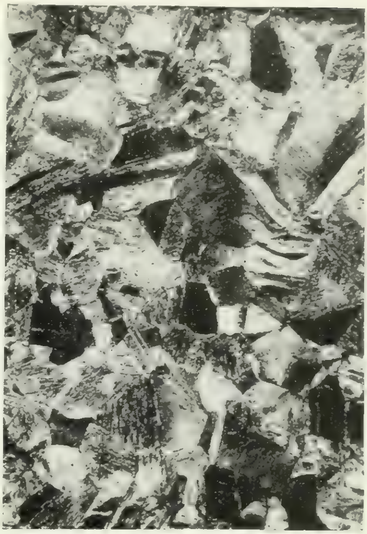


FIG. 10.—Hard Drawn Material, Cross Section. (× 75.)

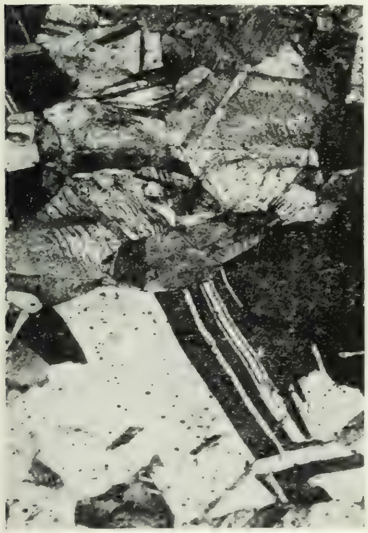


FIG. 11.—From Split Section showing Marked Variation in Grain Size and the Effects of Cold Working. (× 75.)

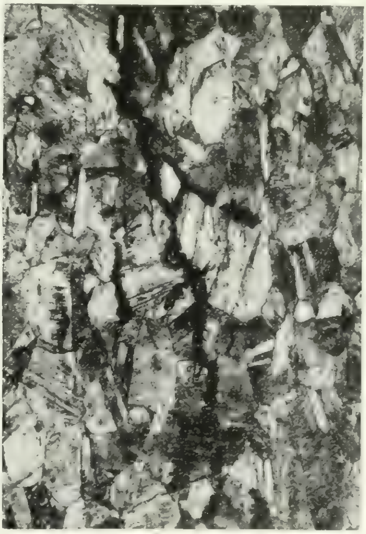


FIG. 12.—Typical Season Cracking and Grain Distortion. (× 75.)

in the form of irregular cracks varying from longitudinal to transverse, all showed more or less distortion of grain,

Fig. 12 is typical of such material. The crack follows the grain boundaries. In these tubes there is a variation from very coarse to very fine grain size,

Twelve samples of split condenser tubes were taken at random and sections about 3 in. long were cut from the sound portion of each. These were immersed in mercurous-nitrate solution with the expectation that cracks would develop. Eleven of the samples showed no sign of failure after fifteen minutes in this solution. The twelfth sample split wide open at the end of one minute with an irregular crack. These results were therefore negative and showed that either these longitudinal cracks are not due to internal strains revealed by the mercurous-nitrate test or that the strains were localized and were relieved by the splitting of the tube.

Only the one sample which split during the mercurous-nitrate test showed internal strain. Another sample of this tube was annealed at 250° C. for three hours, after which it was immersed in the mercurous-nitrate solution for fifteen minutes without developing cracks. It is to be noted that this material originally showed a coarse grain structure with marked distortion due to cold working (Figs. 9 and 10). A further test was made on a piece of 2-in. brass pipe which had already developed typical season cracks. Two sections from the solid metal were immersed in a mercurous-nitrate solution for fifteen minutes without developing any cracks.

It would therefore seem that the above-mentioned longitudinal cracks in condenser tubes which showed little signs of cold working were due to strains set up in the tube during actual service.

There can be no doubt, however, that cracks are most prone to occur in streaky material, such as shown in Figs. 6, 7 and 8. While it is true that most of the split tubes show more or less streakiness, yet several samples which failed were found to be of perfectly clean brass, such as shown in Figs. 2, 3 and 4.

THE CAUSES AND PREVENTION OF CORROSION CRACKING.

BY W. H. BASSETT.[1]

From times as far back as its traditions go, the brass industry has been troubled with the so-called "season cracking" and "fire cracking" of various forms of brass and bronze. Such cracking occurs only in sections which have been hardened by cold working. The nature of this sort of cracking, and its causes have been fully discussed by Heyn and Bauer,[2] by Martens-Heyn,[3] and by Heyn in the 1914 May lecture before the Institute of Metals.[4]

Season cracking was undoubtedly so called because of the resemblance in appearance to the cracking of wood during seasoning. The name is unfortunate, because misleading. Such cracking is apparently always accompanied by corrosion, and occurs only in material made hard by physical deformation. It is, consequently, the result of internal strains localized in effect by corrosive action.

Fire cracking is very similar in its effect. It is brought about by a very sudden change of temperature, such as that produced by bringing a hard-drawn tube or rod suddenly into a red-hot furnace, or in a spun or drawn shell in contact with a rapidly moving polishing wheel or belt. As in the case of corrosion cracking, the crack generally follows between the crystals or grains of the metal.

Both sorts of cracking occur in copper-zinc alloys containing less than 80 per cent of copper, and perhaps more readily in the alloys containing the higher ranges of zinc. Pure copper, and copper-zinc alloys containing more than 80 per cent of copper, have never been known to crack in this way.

Copper-zinc-nickel alloys, generally known as Nickel Silver, are subject to such cracking, but the copper-nickel alloys without zinc do not crack, unless they contain embrittling impurities.

---

[1] Technical Superintendent and Metallurgist, American Brass Co.

[2] "International Zeitschrift für Metallographie," 1911.

[3] "Materialenkunde für den Maschenienbau."

[4] *Journal*, Inst. of Metals, Vol. XII, 1914, p. 3 (1914).

Copper-tin and copper-aluminum alloys, when made very hard by cold deformation, are subject to corrosion cracking and fire cracking. Such alloys, when rich in copper, do not seem to be subject to such cracking, but those containing relatively considerable amounts of tin or aluminum are rather sensitive to it. Experience has not so definitely shown the tin or aluminum limits, as it has in the case of zinc.

With wrought brasses in the Alpha phase, the cracks always pass between crystals. (Fig. 1.) (In some cases a few crystals on the line of the break may be fractured.)

When both the Alpha and Beta phases are present, the cracks pass through the Beta. (Fig. 2.)

When the alloy is entirely in the Beta phase, the cracks generally pass across the crystals. (Fig. 3.)

That the most important cause of the spontaneous cracking of brasses is internal strains is undoubtedly true, but this cracking also appears to be due to corrosion. No case of such cracking, so far as the writer is aware, has been observed where both internal strains and corrosion were not factors. Brasses which are kept polished do not crack. Brasses stored in a dry, clean atmosphere, although carrying high internal strains, crack only after a long time. Damp atmosphere is especially active in producing such cracking, particularly if it carries ammonia vapor from decaying organic matter, or sulfurous acid gas from burning coal. Brass hardened by cold working, if the strains are not relieved in some way, is apt to crack if used near railroad terminals where coal burning locomotives are employed. Such material, if stored over winter in stables or boat houses, not infrequently gives way.

Spun or drawn brass lamps, on carriages and other vehicles, sometimes break during winter storage in stables, on account of condensation of moisture during periods of rising temperature, with absorption of ammonia from the atmosphere.

In cases of the cracking of brass water pipes, the trouble is generally with the cold water pipe in the cellar where condensation takes place on the surface due to the damp atmosphere, and the cooling of the pipe by the water within. In such cases the cracking proceeds from the outside surface inward.

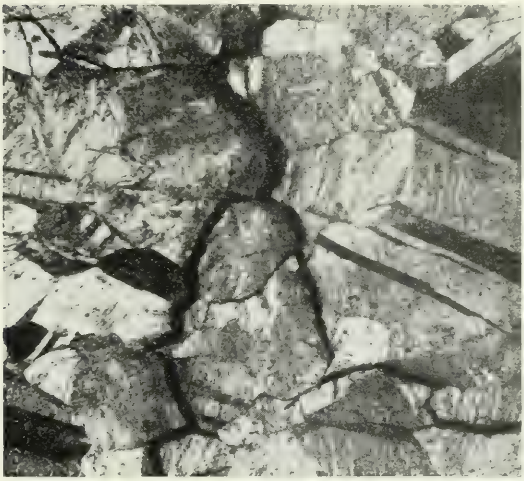


FIG. 1.—Cracks between Alpha Crystals. Copper, 67.32 per cent; Zinc, 32.20 per cent; Lead, 0.43 per cent; Iron, 0.05 per cent. (× 75.)

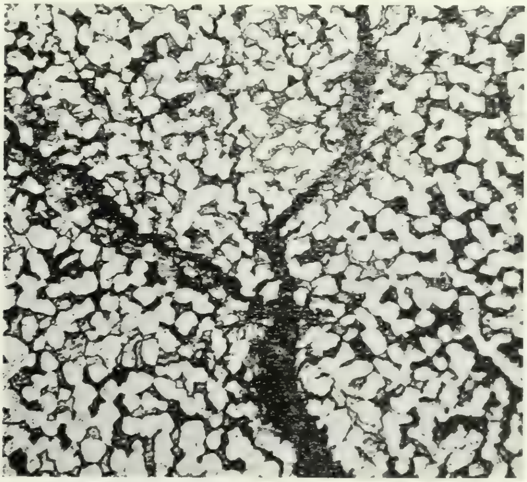


FIG. 2.—Cracks passing through Beta Constituent in Naval Brass. Copper, 60.49 per cent; Zinc, 38.64 per cent; Tin, 0.76 per cent; Lead, 0.08 per cent; Iron, 0.03 per cent. (× 75.)

ETCHING SOLUTION: Hydrogen Peroxide and Ammonia.

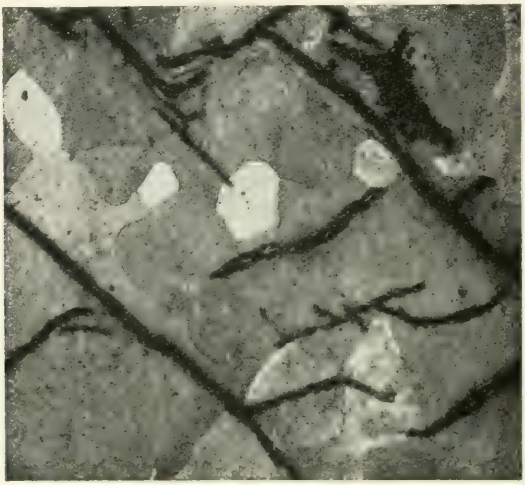


FIG. 3.—Cracks passing through Beta Crystals. Copper, 55.38 per cent; Zinc, 43.74 per cent; Tin, 0.78 per cent; Lead, 0.07 per cent; Iron, 0.03 per cent. (× 75.)

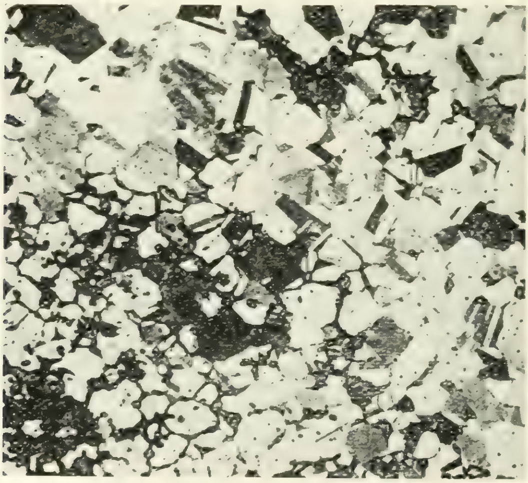


FIG. 4.—Surface Corrosion between Crystals. Copper, 66.54 per cent; Zinc, 32.68 per cent; Lead, 0.74 per cent; Iron, 0.04 per cent. (× 75.)

ETCHING SOLUTION: Hydrogen Peroxide and Ammonia.

Winter storage of rods and tubes in unheated sheds on docks has occasioned trouble with brass carrying high internal strains. Generally speaking, corrosion-cracked brass will have a tarnished or dirty surface, but seldom shows visible corrosion. Microscopic examination generally reveals corrosive action between the crystals of such brass. (Fig. 4.)

Even the air of a humidity chamber brought close to the saturation point by warming distilled water with a partly immersed electric-light bulb is sufficient to start intercrystallin corrosion, and considerably accelerate the cracking of very hard drawn brass or nickel silver.

There are very few definite data concerning the effect of the addition of elements other than copper and zinc to brasses. Experience indicates that cracking is more frequent in brasses carrying a higher percentage of zinc. Zinc is the hardening element, and the magnitude of the strain set up in a given section for a certain amount of distortion is greater the higher the percentage of zinc present. Zinc is also the element more readily attacked by chemical action.

There is no evidence to show that lead, tin, iron, or other common impurities, or frequently employed addition elements, have any marked effect, either in increasing or decreasing the tendency of brass to crack from internal strains, except that they may help in its prevention by decreasing corrodibility. Experience does not indicate any effect by such elements, except through increasing resistance to corrosion, although the question of their possible effect has been frequently raised. It is, of course, probable that any element which decreases ductility, or increases the hardening effect of cold deformation, or increases corrodibility, may to some extent increase the tendency to crack under favorable conditions. In a number of cases where material had cracked, analyses have been made to detect the presence of such impurities as antimony, bismuth and cadmium, which could possibly have an embrittling effect when present even in small quantities. The work was undertaken in such a way as to determine such impurities to 0.01 per cent, and to readily recognize 0.001 per cent. Antimony was found in some cases up to 0.001 per cent, which can be accounted for by its presence in the electrolytic copper used; bismuth has never been found; and cadmium amounting to 0.02 per cent, or less, has been found in some samples, and not found at all in others.

The fact that corrosion cracking occurs in hard brass made from Lake copper, which does not carry even traces of antimony or bismuth, and cadmium-free zinc, may be cited as further evidence that this trouble is not primarily caused by such impurities. For instance, cartridge brass and shell head stock covering the range from 75 per cent copper and 25 per cent zinc, to 66 per cent copper and 34 per cent zinc, and prior to the present war always made from the purest brands of Lake copper and zinc from the Bertha or New Jersey mines, has frequently given trouble of this nature.

The best spring brass stock from 72 per cent copper and 28 per cent zinc, and made with copper and zinc from the same sources as the cartridge brass just mentioned, frequently gave trouble from cracking. This was so well recognized by spring makers that it was customary never to let such brass remain in storage, but to make it into springs as soon as received, in order that the working given the metal in forming it would break up the strains and prevent cracking.

Table I.—Composition of Samples.

Bar No.	Analysis No.	Copper, per cent.	Zinc, per cent.	Lead, per cent.	Iron, per cent.	Cadmium, per cent.
1	68 862	69.48	30.44	0.02	0.06	0.000
2	68 863	69.05	30.87	0.02	0.04	0.016
3	68 864	70.01	29.87	0.02	0.03	0.073
4	68 865	70.33	29.58	0.01	0.04	0.036
5	68 866	69.55	30.29	0.01	0.02	0.130
6	68 867	69.01	30.74	0.01	0.03	0.208

In order to investigate the merits of the oft-repeated assertion that the cadmium impurity carried by zinc from mines in the Central and Western states might possibly increase the liability to season cracking, we had a series of melts made from 70 parts of Lake copper and 30 parts of cadmium-free zinc, with the addition of varying proportions of pure cadmium used in the form of a 90 and 10 zinc-cadmium alloy. It was intended to secure a series of six alloys containing from zero to 0.25 per cent of cadmium, but on account of the volatility of the cadmium, the maximum amount secured was 0.208 per cent. The compositions of the samples determined by analysis are given in Table I.

The bars were cast 1 in. thick by $3\frac{3}{4}$ in. wide, and finished to 0.013 in. thick by $3\frac{15}{16}$ in. wide. The material was all annealed together and drawn into shaving-stick boxes of the usual type, embossed with lettering on the side, and beaded at the bottom and one-half inch from the top. These operations left the metal in a state of very unequal strain. Fifteen boxes from each lot were buffed, cleaned, and inverted over wooden pegs in a board, which was placed out of doors, close to the Naugatuck River, at a point where this stream was badly polluted with city sewage and factory waste.

These drawn shells were inspected every day for one month and then every other day until three months had passed, and finally monthly.

The results of inspection are given in the following table:

BAR NO.	FIRST CRACK AFTER
1	22 days
2	5 "
3	6 "
4	12 "
5	6 "
6	5 "

The number of shells found to be cracked after one month and seven months are given below:

BAR NO.	NUMBER CRACKED AFTER ONE MONTH.	NUMBER CRACKED AFTER SEVEN MONTHS.
1	1	5
2	3	4
3	2	2
4	2	2
5	2	3
6	6	11

It is true that the brass containing no cadmium was somewhat slower to crack than the others, but it is also true that after seven months' exposure, it was in worse condition than any of the others except the one containing the largest amount of cadmium.

Apparently cadmium increases, rather than decreases, the ductility of brass. This may be noted from Table II, showing the physical properties, after four different heat treatments, of test samples from the series of six lots of sheet metal from which the shaving stick boxes were made.

The increased ductility due to cadmium in brass is also shown by the results of testing sheet brass, lots A and B, after annealing together at several temperatures. The compositions of these two lots as determined by analysis are as follows:

TABLE II.—PHYSICAL PROPERTIES OF TEST SAMPLES, WHOSE COMPOSITIONS ARE GIVEN IN TABLE I.

Bar No.	Cadmium, per cent.	Temperature at which Annealed, deg. Cent.	Tensile Strength, lb. per sq. in.	Reduction of Area, per cent.	Elongation in 2 in., per cent.
1	0.000	450	53 550	73	43.8
2	0.016	"	52 850	71	44.8
4	0.036	"	53 350	78	41.0
3	0.073	"	53 650	78	44.5
5	0.094	"	53 200	80	43.5
6	0.208	"	53 100	62	44.0
1	0.000	550	48 900	70	50.3
2	0.016	"	48 400	76	50.5
4	0.036	"	49 400	76	50.0
3	0.073	"	48 750	67	50.0
5	0.094	"	48 850	71	50.3
6	0.208	"	49 200	72	52.8
1	0.000	650	45 350	78	57.8
2	0.016	"	44 950	73	58.0
4	0.036	"	45 900	75	56.5
3	0.073	"	45 350	74	55.5
5	0.094	"	45 050	78	58.8
6	0.208	"	45 050	73	57.5
1	0.000	750	43 350	74	60.0
2	0.016	"	42 550	71	59.8
4	0.036	"	43 100	71	57.0
3	0.073	"	42 900	77	58.5
5	0.094	"	42 650	72	60.0
6	0.208	"	42 450	68	61.0

	LOT A.	LOT B.
Copper, per cent	66.77	66.97
Zinc, per cent	32.48	33.02
Lead, per cent	0.02	0.02
Iron, per cent	0.01	0.01
Cadmium, per cent	0.72	0.00

Lot B was made from Lake copper and cadmium-free zinc, and Lot A from the same materials with the addition of metallic cadmium, and contained considerably more cadmium than would ever result from the use of any of the grades of zinc in the American market.

The physical properties indicate a higher ductility for the alloy containing cadmium, as may be observed from Table III.

While there is no direct proof to offer, from the nature of the case, and from general considerations, it seems evident that the more ductile material is less liable to cracking on account of internal strains.

The prevention of corrosion cracking becomes a very important subject, since, in order to take advantage of the higher strength and elastic limit obtained by cold working, brass and similar alloys must be frequently used in the hard, or unannealed, condition.

TABLE III.—PHYSICAL PROPERTIES OF TWO ALLOYS.

Annealing Temperature, deg. Cent.	Time, minutes.	Tensile Strength, lb. per sq. in.	Elongation in 2 in., per cent.
LOT A.—CONTAINING 0.72 PER CENT CADMIUM.			
Hard	..	66 690	14.5
500	15	51 345	55.25
552	15	48 650	62.75
660	15	44 886	72.5
750	15	41 148	75.3
850	15	41 515	75.0
850	45	32 390	29.5
LOT B.—NO CADMIUM.			
Hard	..	71 980	9.0
500	15	51 290	53.0
552	15	47 675	58.75
660	15	44 681	66.3
750	15	42 037	73.3
850	15	40 280	71.0
850	45	36 620	39.5

Frequent polishing will prevent cracking by preventing corrosion. This is, of course, impossible in the case of structural material. Annealing is a certain preventative, but, as just indicated, there are many conditions where this cannot be resorted to, on account of the softening effect which reduces the tensile strength and elastic limit of the alloy.

Heyn[1] has discussed the question of relieving internal strains by low temperature annealing; that is, by heating for a time at a temperature below that at which re-crystallization begins, or at which the elastic limit is reduced. Mr. Price's contribution to this discussion gives a very good illustration of this method of prevention.

---

[1] *Journal*, Inst. of Metals, Vol. XII, p. 19–21 (1914).

Much may be done to prevent fracture due to internal strain and corrosion by regulating the deformation in such a way as to diminish these strains. In drawing shells, if the space between die and plunger allows the metal in the sides of the shell to thicken, so that the metal is thicker in the sides than at the bottom, there is a very strong tendency toward corrosion cracking, with the expansion of the sides of the shell. If there is considerable pinch in the drawing, so that the walls of the shell are not thickened, but extended lengthwise, the shells very seldom crack under any ordinary exposure to corrosive action.

To prevent the fire cracking of spun or drawn work, it has been customary to hammer it all over to break up strains.

Drawn rods are straightened by rolling transversely in a straightening machine. This operation reverses the direction of the internal strains, and produces material which will withstand the mercurous nitrate and weathering tests, and which does not crack in service.

Experiments have been made by cutting pieces from drawn Naval Brass rods and straightening the balance of the rod by transverse rolling. The pieces cut from the drawn rod cracked within a few seconds after immersion in an aqueous solution containing 100 g. of mercurous nitrate and 13 cc. of nitric acid (sp. gr. 1.42) per liter, while samples cut from the rod after straightening by transverse rolling did not crack after several hours' immersion. Duplicate samples were exposed to weathering. Those taken before straightening cracked within a month, while those taken after straightening still show no signs of cracking after more than two years' exposure. Years of experience confirm these tests.

Coiling and straightening, and various methods of springing may be employed to secure similar results.

The work of Professor Heyn previously alluded to, and of Dr. Merica of the U. S. Bureau of Standards, has done much toward bringing about an understanding of what was formerly considered a rather mysterious phenomenon. This work has also indicated the reason for, and more intelligent application of, methods of prevention.

SEASON CRACKING.

By W. Reuben Webster.[1]

The phenomenon known as season cracking, which occurs in connection with the employment of wrought brass, has been known for a long time. It has been pretty generally recognized that the primary cause of it is the unequal distribution of stresses in the interior of the material, set up by the processes of cold working. It has also been recognized for some time that a contributing cause was some species of corrosion. One of the baffling circumstances connected with the manifestation of this was the erratic nature of its occurrence. There seems to be no way of predicting whether a specific material will or will not exhibit the difficulty under any particular set of conditions. It has also been known that material which had been annealed, or partially annealed, was not subject to this trouble.

In the manufacture of wrought brass an analogous difficulty is experienced, known as fire cracking. This manifests itself by the occurrence of cracks in material which has been subject to cold working, when such material is heated in an annealing furnace. This latter difficulty is prevented by employing an operation known as springing, which consists in so distorting the wrought material as to equalize or change the direction of the internal stresses. Similar treatment has been found to be efficacious to a marked extent in preventing season cracking, but the need of some test which would determine whether such stresses existed to a degree sufficient to cause trouble from this source has long been recognized.

It has been proposed to employ a solution of mercurous nitrate, into which samples are to be dipped. In case of the existence of internal strains, this test will very quickly detect them. Some experience with the test, however, has indicated that it is too severe. In order to determine this fact, a miscellaneous assortment of wrought-brass products were submitted to the test, applied in the manner recognized as standard. The products consisted of miscellaneous stamped and drawn brass articles, such as lamp parts, bicycle pumps, automobile hub caps, etc., also brass rods and sheet brass. All of the articles employed in this test are commercial articles, with the use of which everyone is familiar, and concerning the performance of which complaints have very seldom if ever been reported. Of these, 25 were injured and 11 showed no effects of the solution. It is therefore quite evident that this test is not one which can be given general application, and should be confined to materials which are to be employed in circumstances where difficulty due to season cracking is to be anticipated. It is certain that a great variety of articles which are employed to satisfy daily needs, which experience demonstrates conclusively do so without trouble from season cracking, would not stand this test.

---

[1] Superintendent, Bridgeport Brass Co.

Several samples made on screw machines from brass rod which showed small cracks on being tested, all withstood the mercury test successfully, although the amount of material removed by the machining operation was relatively small.

INITIAL STRESS AND CORROSION CRACKING.

By P. D. Merica and R. W. Woodward.[1]

Season cracking of brass was first described by Diegel in 1906,[2] but it has not been until more recently that an epidemic of brass bolt failures of this type experienced by the New York Board of Water Supply[3, 4] in the construction work of the Catskill Aqueduct, by the Engineers' Department of the city of Minneapolis[4] in the construction of the filtration plant and by others, has engaged for it the attention from metallurgists and engineers which it properly deserves. Recently also the phenomenon has been observed in the case of cartridge cases and of condenser tubes;[5] it is not limited in its occurrence to any form or shape of brass article, but has been known to occur in drawn, in rolled, in forged, in spun and in cast metal. Apparently it is brass of composition between 45 and 20 per cent of zinc that is principally subject to it. Not only brass of these compositions but also other metals such as nickel silver, nickel steel, aluminum, aluminum bronze and other alloys have been shown to be subject to it.

The characteristics of season cracking are now too well known to require extensive description. Metal which is sound and of excellent mechanical properties, as measured in the usual manner, develops cracks after manufacture, often while in storage and before the application of any external load or stress. Investigation has shown that this cracking is primarily due to the presence of internal stresses, initially present in the manufactured article,—rod, tube or sheet,—the effect of which in producing cracking is realized in general only through the secondary agency of surface corrosion. Bars or tubes, with excessive initial stresses, which will season crack when exposed to atmospheric corrosion, will not crack if their surface is protected, by oiling or otherwise, from the corrosive action.

---

[1] Assistant Physicists, U. S. Bureau of Standards.

[2] Diegel, Nachträgliches Reissen Kaltverdichteter Kupferlegierungen; Verh. d. Ver. z. Bef. d. Gewerbefleisses, Vol. 85, p. 177 (1906).

[3] A. D. Flinn, "Brass in Engineering Construction," *Engineering Record*, Vol. 68, p. 527 (1913).

E. Jonson, "Failures of Forgible Brass Bars," *Transactions*, Am. Inst. Metals, Vol. 8, p. 135 (1914); also, "Fatigue of Copper Alloys, *Proceedings*, Am. Soc. Test. Mat., Vol. XVII, Part II," p. 101 (1915).

[4] P. D. Merica and R. W. Woodward, "Failure of Brass", Bureau of Standards *Technologic Paper No. 82*, 1917; also, *Transactions* Am. Inst. Metals, Vol. 9, p. 298 (1915).

[5] A. E. White, "An Investigation Leading to Specifications for Brass Condenser Tubes," *Proceedings*, Am. Soc. Test. Mats., Vol. XVI, Part II, p. 151 (1916).

The influence of corrosion in the acceleration of failure by cracking of brass under direct, applied tensile stress has been demonstrated by Jonson[1] and an explanation of this effect of combined stress and corrosion, given by Merica[2]. Although it is essentially a ductile material, a bar of brass under tensile stress will crack and finally facture, when simultaneously being corroded by ammonia solution, at a value of the stress considerably below that of the ultimate tensile strength of the metal, and with a fracture characteristic of a brittle material. This anomalous behavior is due to the surface roughening or notching caused by the corrosion, and the extension of these minute notches as sharp cracks into the interior of the bar; the growth of the cracks in this manner is occasioned by the fundamental fact that the application of tensile stress to brass increases its electrolytic solution potential.

Variation of temperature as well as surface corrosion may be the secondary factor which brings about the cracking of initially stressed brass. "Fire cracking" of drawn brass when put into the annealing furnace is an allied phenomenon similar to season cracking and is quite well known to the manufacturer. Speaking approximately only, material which is sufficiently initially stressed to fire crack, will also ultimately season crack.

The more exact definition of this phenomenon of season cracking, which has been the result of recent investigation, and the resolution of its cause into the two chief factors noted above, would render the term "corrosion-cracking" a more suitable general one to apply to it than the older and more vague one of season cracking. This term has the sanction, it is believed, of several of the brass manufacturers.

---

[1] *Loc. cit.*

[2] P. D. Merica, "Effect of Corrosion on the Ductility and Strength of Brass," Bureau of Standards *Technologic Paper No. 83.* (1916).

ORIGIN OF INITIAL STRESS.

Initial stress, the primary factor in either corrosion or fire cracking, may be introduced into a material in several ways and in several modes of distribution. It is to be noted that obviously, the summation of initial stress through any full, plane section of a material must be zero; for every tensile stress there must be an equal and opposite compressive stress. In almost all cases, the introduction of initial stress is due to the fact that some operation of manufacture, be it heating, rolling or mechanical working, is not applied uniformly to every portion of the article.

Thus, the non-uniform cooling of different portions of an article from a high temperature leaves initial stress in it; that part which cools most rapidly is, speaking generally, left in compression; the remainder, in tension. This fact is of course well known to founders of metal, who are obliged to take care of this difference thus produced in the rate of shrinkage of castings, often by special methods.

The welding or burning-in of castings or other articles will also generally produce initial stress in the cooled piece, the welded portion being in tension parallel to the surface and perpendicular to the weld.[1]

If a round bar of brass is suddenly cooled by quenching from a high temperature, the outer half of the cross-section will be left in longitudinal compression, the inner half in tension. Measurements have shown that in 1-in. round bars of naval brass and manganese bronze, quenching from 450° C. into water produces an average longitudinal, initial compressive stress over the outer half of the cross-section of 14,500 lb. per sq. in.

Initial stress is also produced by mechanical means, particularly cold working, and initial stress produced in this manner is the cause of most corrosion cracking. In drawing a tube or bar through a die, the stress caused by the pressure of the plunger or the pull of the tongs is unequally distributed across the section immediately under the die; the portion of the metal just emerging from the die and in immediate contact with it carries more of the load per unit section than the central portion. This inequality of stress distribution persists upon removal of the pulling load or plunging pressure, leaving the outer layers of the tube or rod in tension, the inner, in compression, parallel to the direction of the draw. In rolling or forging under the hammer the exact converse is true; the lateral compression at the section just entering the rolls, for instance, is taken chiefly by the surface layers, which retain this upon emerging, the inner portion being thereby placed in tension.

---

[1] P. D. Merica and C. P. Karr, "Initial Stress Produced by the Burning-in of Manganese Bronze," Bureau of Standards *Technologic Paper No. 84* (1916); also, *Transactions* Am. Inst. Metals, Vol. 10, p. 90 (1916).

Initial stress, finally, may result from some operation, cooling or working, which though uniformly applied to all portions, is applied to a material which is itself not uniform throughout in its composition or properties. Thus, the sudden cooling of a heterogeneous material such as ordinary 60–40 brass, consisting of two constituents—the alpha and the beta solid solution—possessing quite unequal coefficients of thermal expansion, undoubtedly leaves the particles of the alpha constituent in hydrostatic compression and those of the beta constituent in tension, tangential to the boundaries of separation. Computations based upon measurements of these thermal expansion coefficients[1] indicate that such stresses may amount to 16,000 lb. per sq. in. or more.

The practical problem which the phenomenon of season cracking places before the metallurgist is a three-fold one: first, the development of methods for the determination or indication of the extent and distribution of the initial stresses; second, the determination by those methods of the maximum safe limits of such stresses through correlation with service tests; and third, the discovery of methods of manufacture by which either the introduction of the stresses may be avoided or whereby after introduction these stresses may be removed without detriment to the other properties of the material and at the least expense.

MEASUREMENT OF INITIAL STRESS.

The direct measurement of initial stress in articles is at best an operation requiring much care; it is often practically impossible owing to the complex distribution of the stress.

---

[1] P. D. Merica and L. W. Schad, Bureau of Standards *Scientific Paper No. 321* (1918); also, *Journal*, Am. Inst. Metals, Vol. 11, p. 396 (1917).

The measurement of initial stress in round bars, rolled or drawn, is of all such measurements perhaps the most readily accomplished owing to the fact that the initial stresses in such a bar are principally symmetrical to the axis. Howard[1] and later independently Heyn[2] have described the most accurate method for such measurements; measurement is made of the length of such a bar after the removal of successive concentric layers on the lathe, calculation of the average stress in each layer removed may be made from the changes of length so produced and the modulus of elasticity of the material. Since it is desirable in such a stress survey of a bar of ordinary length to be able to measure the change of length to 0.0001 in., a line or end comparator must be used in the length measurements. The stresses in each layer thus determined may be graphically plotted as a function of the distance of the layer from the axis of the bar, as illustrated later in Fig. 2.

Inspection of the plotted values of initial stress shows that there is a neutral fiber layer much as in the case of beam flexure. The summation of stresses on either side of this neutral fiber in general will exactly balance each other and the average value of the tensile stress will be equal to the average value of the compressive stress, although their maximum values may be different. The measurement of this average value of the initial stress (equals the total tensile force divided by the total area under tension, equals the total compressive force divided by the total area under compression) is made very simply by noting the change in length which occurs when an annular layer is removed exactly down to this neutral fiber layer. If the distribution of stress is unifrom and symmetrical, which can generally be assumed, the neutral layer will be at 0.7 of the original cross-section. Because of the larger differences in length encountered in this latter method it will be found possible to use an ordinary strain gage instead of the comparator referred to above. This greatly simplifies the determination, as at best the complete survey of initial stress with a comparator will take four or five days and is a tedious operation.

---

[1] Howard, "Test on Harveyized Bars," Tests of Metals, Watertown Arsenal, p. 285 (1893)

[2] E. Heyn, "Materialienkunde für den Maschinenbau," IIA, by A. Martens and E. Heyn, 1912.

An alternative method of measuring the stress in a bar is by boring out successive cylinders of metal beginning at the center and noting the length changes caused thereby. This method is not to be preferred to the other for the reason that the former method analyzes the stress distribution at the surface of the bar more in detail, where these stresses are effective in producing cracking.[1]

Any regular bar stock of section other than round can be surveyed for initial stress by removing layers in a shaper, milling machine, or other machines as the case may be, but for very small sections which cannot be readily machined it is necessary to remove the layers with acid. Nitric acid diluted with two parts of water has been found satisfactory for this purpose. The attack of the acid does not leave a smooth surface and the accuracy of the results is greatly reduced by this method.

Thus small tubes can be plugged up at the ends and etched on the outside surface.

In the case of thin sheets an excellent method of stress measurement is to cover completely a specimen about 6 in. long and $\frac{1}{2}$ in. wide with paraffin except on one of the large surfaces and then etch in acid until exactly one-fourth of the thickness of the sheet has been removed. If there were initial stresses present it will be found that the strip is bent into the arc of a circle. By measuring the middle ordinate of this arc the average value of the initial stress may be computed from the following formula:

$$S = \frac{36\, T \times E \times D}{7\, L^2}$$

in which S = the average initial stress, T = original thickness of the sheet, E = modulus of elasticity, D = middle ordinate of arc after acid attack, L = length of the specimen.

This procedure was followed in measuring the average stress in material used in constructing a brass plate electrical condenser at the Bureau of Standards. This material, which was 0.031 in. thick, had previously been annealed at about 250° F. (120° C.) and it was thought that all stresses were removed. During calibration of the condenser it was noticed that there were still very small erratic changes in capacity which could not be tolerated in work of the highest precision and due undoubtedly to minute displacements proceeding in the brass sheets caused by the initial stress. A strip of the material was treated as above, and a middle ordinate of 0.25 in. found on a length of strip of 6 in. This corresponded to an average tensile stress of about 18,000 lb. per sq. in.

---

[1] *Technologic Paper No. 82* by Merica and Woodward of the Bureau of Standards gives complete description of methods of initial stress distribution.

Another rapid method of obtaining a value of the initial stress was suggested by S. W. Miller of the Rochester Welding Works. This method depends upon the fact that a longitudinal portion cut from a round bar, and having a section of about 30 deg., will bend in such a way that the outer surface, originally straight, will be convex or concave, depending upon whether compression or tension was originally present in the outside layers.[1]

Either of these two bending methods are rapid and are recommended for obtaining quickly an approximate idea of the value of the initial stress.

Measurements of the initial stresses in failed and in sound bars, tubes, sheets, etc., of 60–40 brass, have shown that only those articles corrosion-crack in which the surface layers are under initial tensile stress amounting to approximately 25,000 lb. per sq. in. Articles in which the surface layers are under initial compressive stress do not crack in this manner, as far as we now know.

THE INSPECTION OF BRASSES FOR INITIAL STRESS.

It would seem then that in order to prevent corrosion cracking, we might specify that a measurement, when possible, made by any one of the methods outlined above, should indicate a value of the tensile stress within the surface layer definitely less than that of 25,000 lb. per sq. in.[2] Allowing a suitable margin for safety an upper limit of 15,000 lb. per sq. in. should be required. It is, however, fortunately possible to accomplish approximately the same purpose very much more conveniently by the use of a short cut—the mercury salt solution test. There is a very close parallelism between the behavior of initially stressed brass as regards corrosion cracking when subjected to ordinary corroding agents and when immersed in a solution of a mercury salt; many tests, including the original ones made at the Bureau of Standards and those made elsewhere, have shown that a rod or tube which will crack in this test will also season crack, and conversely. The more exact study and correlation of this test with the results of weather exposure tests has just recently been given some further study, which will no doubt develop much valuable information.

---

[1] For method of calculation see Merica and Woodward, *loc. cit.*

[2] This holds for 60–40 brass; the corresponding value for alpha brass is not known.

The authors therefore believe that the mercury salt solution test, in whichever one of its forms proves to be the most satisfactory, is a very desirable and indeed a necessary one in the testing and inspection of brasses. Is it a sufficient one to provide definitely against the acceptance of material likely to fail subsequently by corrosion cracking?

It is highly probable that this test will eliminate all material which is liable to season crack; its sufficiency in that sense may be regarded as being in the process of demonstration every day. The authors doubt quite seriously, however, whether it is a sufficient test in the same sense for rods, tubes, etc., which are to be subjected to tensile stress in service, such as construction members, bolts, etc. Assume that a rod of naval brass has been finished with a draw without springing and sent out to inspection with moderate initial stresses. If the value of the initial tensile stress in the surface layers is less than the critical value of 25,000 lb. per sq. in.—for example, 15,000 lb. per sq. in.—the rod will not fail in the mercury salt solution test. The rod is passed and is threaded and used as a bolt, a tensile stress of 15,000 lb. per sq. in. being applied to it. If the elastic limit of the material in the outer layers is at least 30,000 lb. per sq. in., that value will be the value of the resultant tensile stress in the outer layer, and as this is above the critical limit established the bolt is likely to crack.

The authors can cite a number of instances in which material, samples of which did not fail in the mercury salt solution test, did crack in service under the application of moderate service loads. The tensile stress at the surface of these articles was not alone sufficient to produce cracking, but when augmented by a moderate externally applied stress, failure occurred. Had there been no initial tensile stress present in the outer layer, failure would undoubtedly have been prevented.

It would seem, therefore, that one should quite clearly distinguish the two cases in applying and interpreting the results of the mercury salt solution test; it may be relied upon in the one case in which the material is subsequently not further to be stressed in tension, but not necessarily in case it is to be so stressed. For the latter case a direct measurement of the initial stress, if possible, is to be recommended, the result to be used in conjunction with the knowledge of the service stress which the article will be called upon to support. The sum of the surface layer initial stress and the externally applied stress should not be in excess of a certain value, which for 60–40 brass could be taken as approximately 15,000 lb. per sq. in. (tension).

As an alternative, to circumvent the difficulty of measuring the value of the initial stress just at the surface, the mercury salt solution test might be carried out with the specimen under the tensile load (plus some marginal excess for safety) for which it was designed in service.

Of late the problem of testing is somewhat simplified, for round bars at least, by the fact that good manufacturing practice insists upon finishing drawn rods in a straightening machine, which as is shown below may introduce a compressive stress in place of the original tensile stress at the surface. An initial stress measurement then only needs to show whether the outer layer is in compression or in tension in order to indicate whether straightening or springing has been properly accomplished. As shown above, such a test may be readily made by the use of a strain gage when machining a tension test specimen.

THE ELIMINATION OF INITIAL STRESS.

In eliminating initial stress in brass two general methods are available. First, the stresses may be removed or reduced to a safe value by annealing at a proper temperature; and second, the stresses may be removed mechanically by some process which introduces a stress at the surface of opposite sign to that already present.

Fig. 1 shows the effect of annealing at various temperatures on the average value of the initial stress of two different samples of manganese bronze.

Curve 1 shows the effect of one hour's annealing on specimen No. 136, a 1-in. round bar of the following composition and physical properties:

Copper, per cent	59.1	Tensile strength, lb. per sq. in.	72 000
Zinc, per cent	39.3	Proportional limit, lb. per sq. in.	27 500
Tin, per cent	0.78	Yield point, lb. per sq. in.	48 000
Lead, per cent	0.13	Elongation in 2 in., per cent	44
Iron, per cent	0.70	Reduction of area, per cent	50

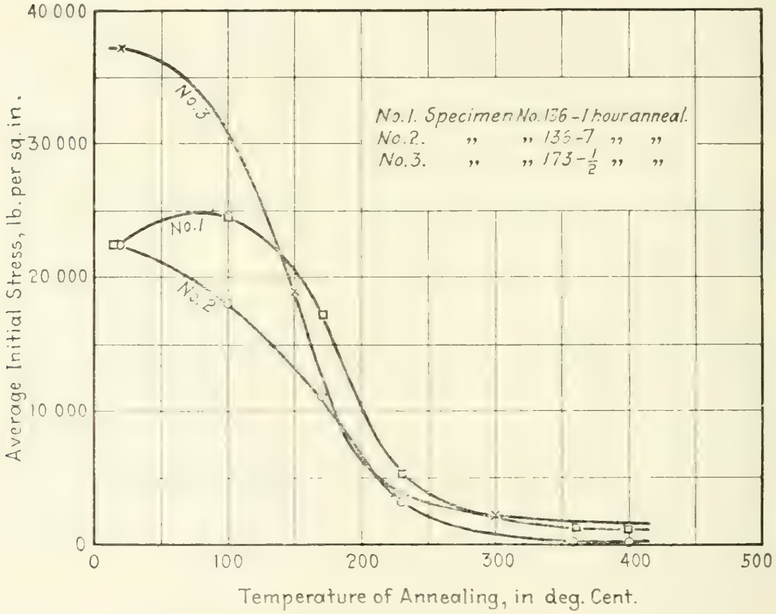


FIG. 1.—Elimination of Initial Stresses in Manganese Bronze Rods by Annealing.

Curve 2 shows the results of 7 hours' annealing on the same material. Curve 3 gives the results obtained on annealing specimen No. 173, a 1-in. round bar of the following composition and properties:

Copper, per cent	56.8	Tensile strength, lb. per sq. in.	100 500
Zinc, per cent	39.9	Proportional limit, lb. per sq. in.	20 000
Tin, per cent	1.63	Yield point, lb. per sq. in.	63 000
Lead, per cent	0.11	Elongation in 2 in., per cent	9
Manganese, per cent	0.22	Reduction of area, per cent	14

The stresses in both materials are sufficiently relieved by annealing at 200° C. It will be noticed that specimen No. 173, which has a considerably greater hardness due to cold working than No. 136, also is relieved of internal strains at a lower temperature than the latter. No. 136 was found not to have softened any after annealing at 400° C., and although No. 173 would probably lose some of its hardness at this temperature, it is not thought that a temperature of 200° C., at which the initial stress is practically removed, would affect the hardness of the material.

It is thus possible to anneal and relieve the initial stresses in brass at such a low temperature that the hardness which it has gained by mechanical working is not affected, an important practical point. On the other hand these annealing temperatures, while readily produced and controlled in the laboratory, are not readily adapted to present commercial practice and equipment.

The mechanical methods of relieving initial strain are therefore the most promising for production purposes, and there are several straightening machines on the market which apparently accomplish this result in a satisfactory manner, at least for rods and probably also for tubes. When a bar is cold straightened by springing—that is, by bending along each radius—the outer layers of the rod or bar are elongated and strained beyond the elastic limit and upon returning to their original dimensions are relieved partially of the initial stress resulting from the drawing; there results a new system of initial stress distribution caused by the springing operation, which is illustrated in Fig. 2, taken from the results of tests made at the Bureau of Standards on samples supplied by Mr. W. R. Webster, Superintendent, Bridgeport Brass Co. Specimens Nos. 1 and 5 were cut from two separate drawn rods, the rods then thoroughly sprung and specimens Nos. 1–S and 5–S cut from the rods. From the curves it will be noticed that the unsprung samples have tensile stresses at the surface, while the effect of springing has been to relieve these tensile stresses and introduce compressive stresses. The average stress in both sprung samples is practically identical and the distribution also not greatly different. In specimen No. 1 the average stress has been reduced from a value which might be considered dangerous to a safe one, and in specimen No. 5 the average value has been increased, although still being within the limit of safety. This would seem to indicate that these samples have both been

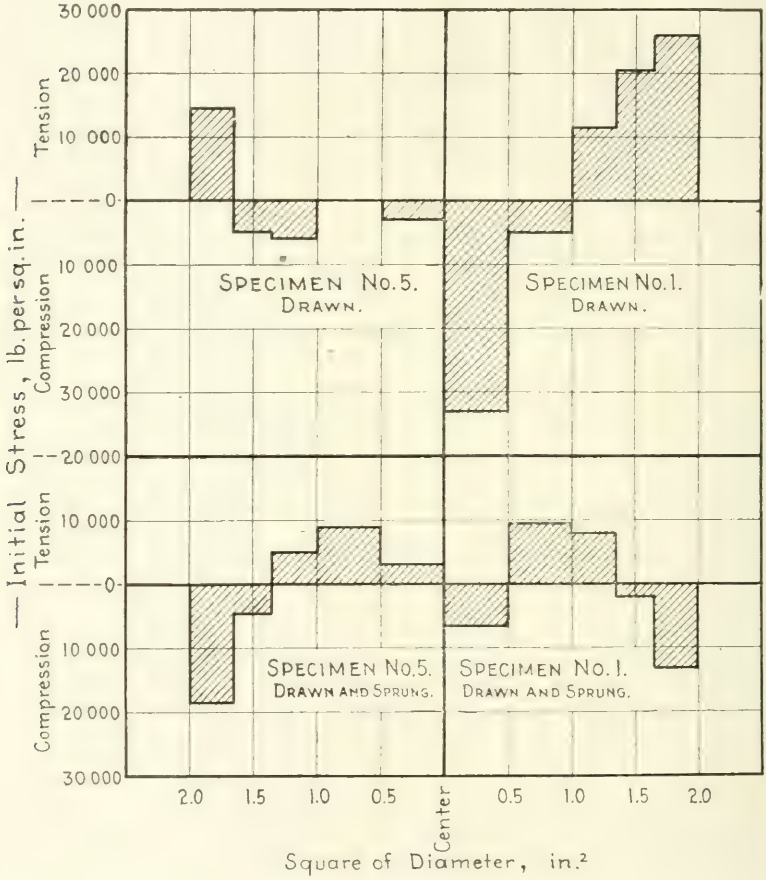


FIG. 2.—Initial Stress Diagrams for Drawn and for Drawn and Straightened High Brass Rods.

"oversprung" and that if the rolls were set further apart, the average stress might be still further reduced. However, it might be added that the compressive stresses at the surface, even if higher than the unsprung tensile stress as in specimens Nos. 5

and 5–S, are more to be desired from a standpoint of freedom from season or corrosion cracking.

It will also be noticed that the effect of springing does not extend equally to the center of the bar but is greatest at the surface. Thus the sprung samples still show a tendency toward the same relative distribution at the center that they possessed in the unsprung condition.

In measuring the diameter of these specimens preparatory to testing it was observed that the diameter of both rods which had been sprung (about 1.415 in.) had been increased by 0.008 in., or 0.6 per cent. This would partly account for the introduction of the compressive stresses at the surface by springing and again indicate over-springing in this particular case.

By giving close attention to the setting of the rolls it is believed that much can be accomplished by this method in relieving initial stresses in round bar stock.

Other methods of eliminating stresses are by alternate cold drawing and cold rolling during the breaking down of a billet and subsequent reduction to finished size, suggested by E. Heyn.[1] The former will tend to produce tensile stresses in the surface layers, while the latter will produce compression, thus leaving a net result of a small average stress. The authors are not aware that this method has ever been tried.

It has been shown above that quenching will produce compressive stress at the surface. A rod which had been so treated after the customary annealing or original extrusion might require a heavier draw in order to produce the critical value of tensile stress at the surface than would a bar which has been slowly cooled, owing to the fact that at the surface the compressive strain would first require to be neutralized by the draw before the introduction of the opposite tensile stress.

It might be inadvisable to apply this procedure to a 60–40 brass because of the liability of retaining a homogeneous beta structure or of introducing the differential alpha and beta stresses mentioned above, although the latter might be broken down upon further cold work. Quenching with subsequent cold-drawing can be safely applied to ordinary alpha brass;

---

[1] *Loc. cit.*

in fact the authors believe that this latter material is often quenched in practice after annealing.

It may be of interest to know that the authors have experiments now in progress at the Bureau of Standards to ascertain directly what values of tensile stress may be regarded as safe for brass rods which are at the same time subjected to corrosion. After the installation of its new draw bench the Bureau will be in position to extend this program to include similar service stress-corrosion tests of rods of graduated values of surface initial stress, and thus to ascertain definitely what combinations of initial and externally applied stress are safe ones for brasses of different compositions and degrees of hardness, and also incidentally to follow more definitely the correlation of such acceleration tests as the mercury salt solution test with service behavior of brass.

THE PREVENTION OF SEASON AND CORROSION CRACKING OF BRASS ARTILLERY CASES BY SPECIAL HEAT TREATMENT.

By W. B. Price.[1]

The most scientific and lucid explanation of Season and Corrosion Cracking ever published was the 1914 May Lecture on "Internal Strains in Cold-Wrought Metals, and Some Troubles Caused Thereby," by Prof. E. Heyn, Director of the Royal Prussian Institute for Testing Materials, Berlin-Lichterfelde, presented before the British Institute of Metals.[2]

All the papers that have appeared on the same subject since, have been based on Heyn's original paper. In his article, Heyn showed that when a cold-drawn brass rod of the composition, copper 57.8 per cent, zinc 40.8 per cent, lead 1.35 per cent, was subjected to a special heat treatment at temperatures varying from 100 to 230° C., the reheating gradually relieved the internal strains, and that this effect became apparent much below the temperature at which the effect of cold-working (increase in tensile strength, increase in elastic limit, and decrease in elongation) was perfectly removed. "Specimens of the rod reheated for 3 hours at temperatures below 100° C. showed cracking when dipped in mercury solution, whereas specimens reheated 3 hours at 100° C. and more stood the dipping test without cracking."

Table I.—Results of Mercuric-Chloride Tests on Finished Cases, not Heat-Treated.

Lot.	Number Tested.	Number Failed.	Character of Failure.
A..........	4	1	Crack on mouth. See Fig. 1, Plate I.
B..........	4	2	Transverse crack on mouth and base. See Fig. 2, Plate I.
C..........	4	1	Transverse crack on mouth. See Fig. 3, Plate II.
D..........	4	1	Longitudinal crack through flange. See Fig. 4, Plate II.

The object of the present paper is to record the experience of the writer in applying the heat treatment recommended by

---

[1] Chief Chemist and Metallurgist, Scovill Manufacturing Co.

[2] *Journal*, Institute of Metals, Vol. XII, No. 2, 1914.

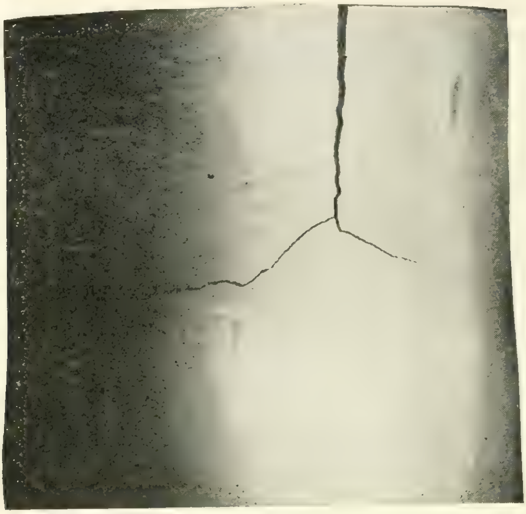


FIG. 1.—Lot A.

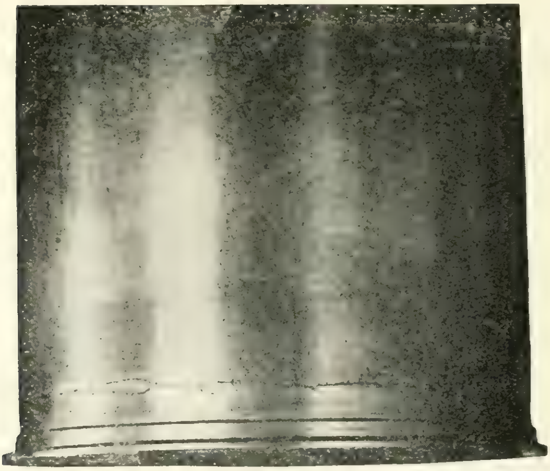


FIG. 2.—Lot B.

PLATE I.—Finished Cases which Failed in Mercuric-Chloride Test.

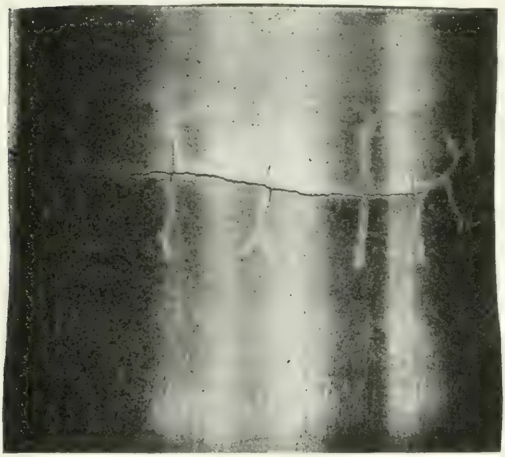


FIG. 3.—Lot C.

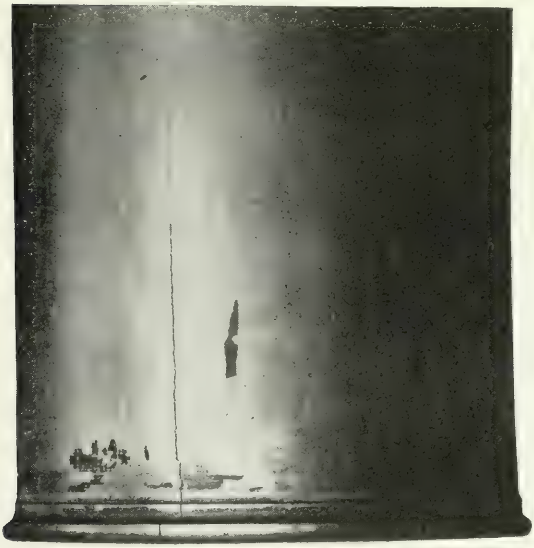


FIG. 4.—Lot D.

PLATE II.—Finished Cases which Failed in Mercuric-Chloride Test.

Heyn to four lots of finished 75-mm. cases, which had cracked at the mouth and base when subjected to the Government test of immersion for a period of 4 hours in a 1.5-per-cent solution of mercury bichloride (corrosive sublimate).

The results of the tests before heat treatment are given in Table I. Figs. 1 to 4, Plates I and II, illustrate the character of cracks which had developed on various lots of finished cases after they had been subjected to the mercuric-chloride test.

HEAT TREATMENT.

A number of shells from each of the four lots were heat-treated for periods of one, two and three hours at a temperature of 500° F. (260° C.) in a Simplex electric oven equipped with a Bristol recording thermometer. The shells to be heat-treated were placed in the hot furnace which was at 500° F. when empty, and after a pre-heating period of a half hour the thermometer read 500° F. Some of the shells were removed at the end of the first, second and third hours of heat treatment. The temperature fell about 60° F. whenever the furnace door was opened to remove a batch. In no case, however, did the temperature exceed the desired temperature more than 15° F.

PHYSICAL CHARACTERISTICS.

Physical tests were made on two cases without heat treatment and on three heat-treated cases, taken from lots A, B and D, with the results given in Table II.

It is very evident from these figures that the heat treatment has apparently not affected the actual physical properties of these cases, as measured by the ordinary testing machine. A temperature as low as 500° F. is not sufficient to cause recrystallization on the greater portion of the shell as manufactured here. Nevertheless, heat treating has certainly diminished the degree of internal strains. Not one of the twelve cases which were tested from each of the four lots, as heat-treated, failed in the mercuric-chloride test. Furthermore, it is certain that the heat treatment has left the cases in a condition to resist corrosion or season cracking on the ballistic test and on long standing. In fact, it is very probable that this heat treatment has even

TABLE II.—PHYSICAL TESTS.

LOT A.

Description.	Location of Section.	Tensile Strength, lb. per sq. in.	Elongation in 2 in., per cent.
Finished case not heat-treated: Case 1	A	52 638	42.8
	B	63 296	23.0
	C	67 200	18.5
	D	62 333	23.2
	E	63 558	22.5[a]
Finished case not heat-treated: Case 2	A	56 338	43.2
	B	70 723	16.0
	C	74 228	15.8
	D	69 304	17.3
	E	61 326	9.0[a]
Finished case heat-treated 1 hr. at 500° F	A	53 663	44.5
	B	64 212	20.5
	C	66 375	16.7
	D	65 053	21.3
	E	63 562	8.5[a]
Finished case heat-treated 2 hr. at 500° F	A	57 010	35.7
	B	68 854	17.8
	C	72 256	15.0
	D	66 425	14.5
	E	62 931	6.0[a]
Finished case heat-treated 3 hr. at 500° F	A	55 985	32.5
	B	65 508	22.7
	C	64 778	24.3
	D	67 027	22.3
	E	62 176	21.5[a]

LOT B.

Finished case not heat-treated: Case 1	A	55 145	45.5
	B	70 877	17.0
	C	74 436	13.2
	D	70 252	16.7
	E	64 341	15.2[a]
Finished case not heat-treated: Case 2	A	52 898	42.7
	B	60 361	27.5
	C	64 498	18.8
	D	61 154	19.2
	E	63 055	9.0[a]
Finished case heat-treated 1 hr. at 500° F	A	54 904	37.8
	B	64 802	21.2
	C	69 177	15.8
	D	67 031	18.5
	E	64 942	14.0[a]
Finished case heat-treated 2 hr. at 500° F	A	55 469	39.3
	B	66 247	20.0
	C	68 347	17.3
	D	65 890	20.8
	E	63 582	14.5[a]
Finished case heat-treated 3 hr. at 500° F	A	50 963	31.0
	B	58 671	27.0
	C	59 899	27.7
	D	58 787	26.2
	E	58 159	39.0[a]

---

[a] Elongation in 1 in.

TABLE II,—PHYSICAL TESTS (*Continued*).

LOT D.

Description.	Location. of Section.	Tensile Strength, lb. per sq. in.	Elongation in 2 in., per cent.
Finished case not heat-treated: Case 1	A	55 920	34.3
	B	69 435	18.0
	C	84 657	11.8
	D	70 575	13.8
	E	67 325	18.0[a]
Finished case not heat-treated: Case 2	A	54 445	30.8
	B	65 937	18.5
	C	81 061	13.2
	D	69 982	17.0
	E	67 156	19.0[a]
Finished case heat-treated 1 hr. at 500° F	A	54 857	36.8
	B	70 759	15.8
	C	86 893	8.3
	D	71 378	14.0
	E	65 296	21.5[a]
Finished case heat-treated 2 hr. at 500° F	A	55 437	18.0
	B	69 118	16.7
	C	83 828	11.2
	D	70 256	12.3
	E	67 770	18.5[a]
Finished case heat-treated 3 hr. at 500° F	A	55 797	15.8
	B	68 115	14.8
	C	83 414	4.8
	D	72 584	13.0
	E	68 496	14.0[a]

[a] Elongation in 1 in.

increased the tensile strength several thousand pounds per square inch. Mathewson and Phillips[1] have shown that heat treatment below the point of recrystallization actually increases the tensile strength of hard-rolled brass.

DISCUSSION OF THE MICROSTRUCTURE.

The heat treatment has not affected the microstructure on the sections as taken according to the U. S. Government specifications. This is illustrated by Plates III and IV. However, a slight recrystallization has taken place near the flange and at a section of the head about ½ in. from the primer hole (see Plate V) after the 2 and 3-hour heat treatments, but does not show it after the 1-hour treatment. This condition is to be expected, because these sections represent the places where the case receives the most work. Recrystallization is a function of the

---

[1] Mathewson and Phillips, "Recrystallization of Cold-Worked Alpha Brass on Annealing," *Transactions*, Am. Inst. Min. Eng., Vol. 54, p. 608, (1916).

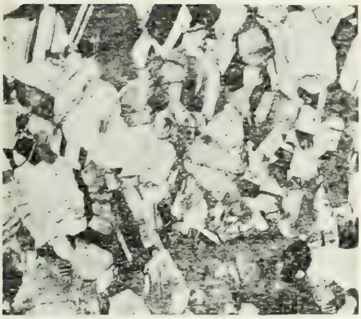


FIG. 5.—Section A.

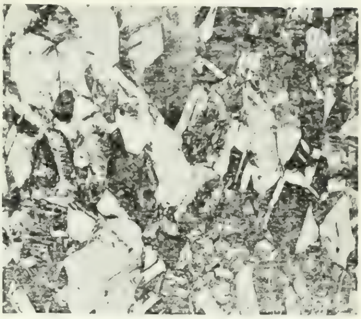


FIG. 6.—Section B.

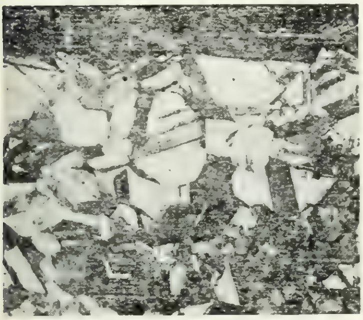


FIG. 7.—Section C.

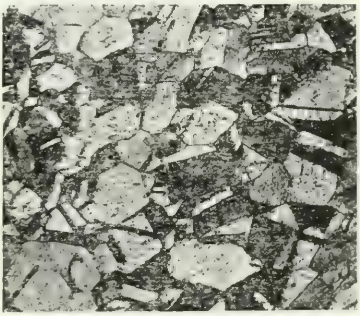


FIG. 8.—Section D.

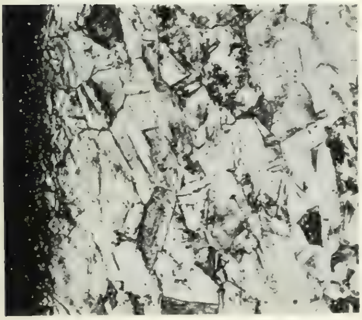


FIG. 9.—Section E.

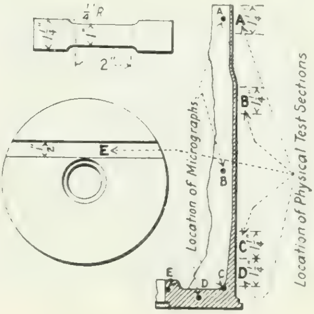


FIG. 10.—Locations of Sections.

PLATE III.—Microstructure of Lot A. Finished Case Not Heat Treated. (×75) Etch: $NH_4OH+H_2O_2$.

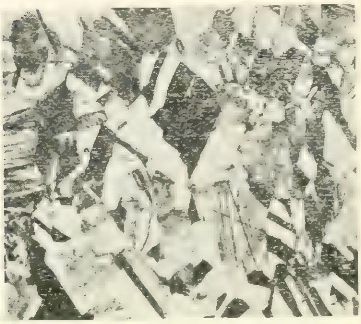


FIG. 11.—Section A.

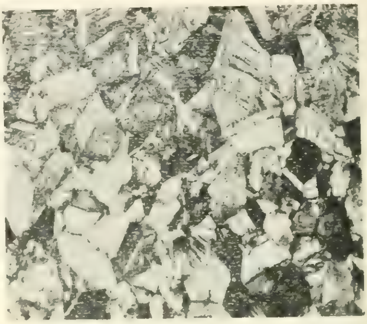


FIG. 12.—Section B.

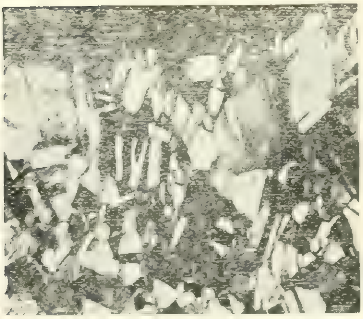


FIG. 13.—Section C.

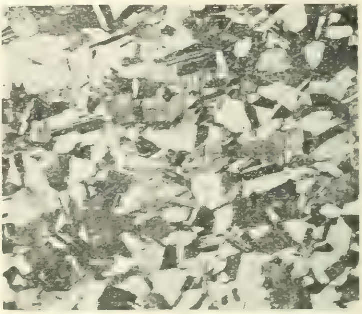


FIG. 14.—Section D.

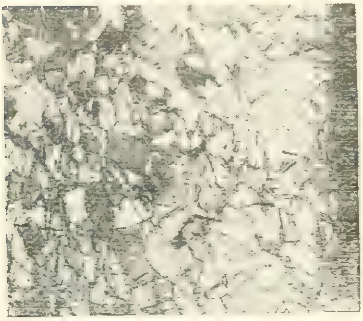


FIG. 15.—Section E.

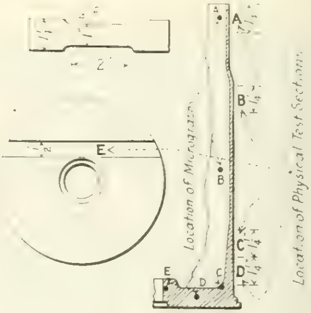


FIG. 16.—Locations of Sections.

PLATE IV.—Microstructure of Lot A. Finished Case Heat-treated 3 Hours at 500° F.
(×75) Etch: $NH_4OH + H_2O_2$.

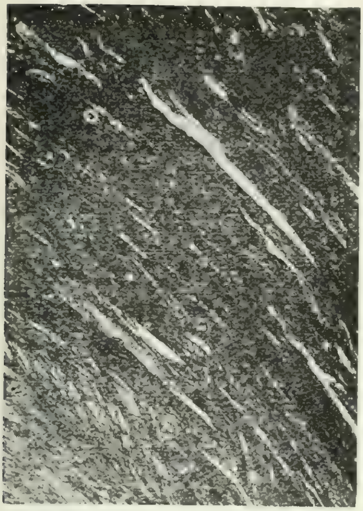


FIG. 17.—Not Heat-treated.

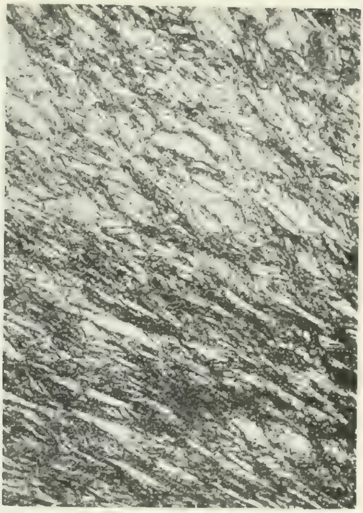


FIG. 18.—Heat-treated 1 Hour at 500° F.

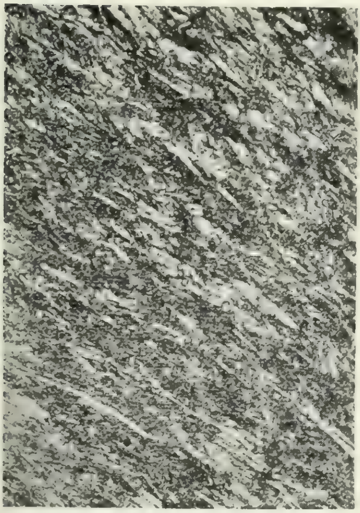


FIG. 19.—Heat-treated 2 Hours at 500° F.

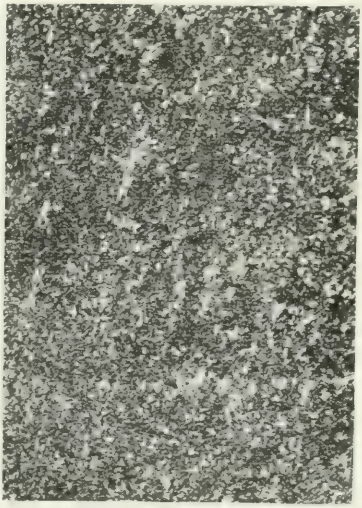


FIG. 20.—Heat-treated 3 Hours at 500° F.

PLATE V.—Microstructure of Flange, Lot A. (×75) Etch: $NH_4OH+H_2O_2$.

temperature and degree of reduction by working, or as Mathewson and Phillips so ably express it: "In order that the heat treatment effect may be felt at a given temperature, it is clear that the mechanical destruction of the original grain must be sufficiently pronounced to produce fragments inferior in size to the recrystallized grain characteristic of this temperature." Although it is true that recrystallization of these particular places has lowered the tensile strength somewhat, this is offset by the fact that internal strains in these areas have been positively reduced, if not entirely eliminated. It is to be noted that a heat treatment of 500° F. for one hour does not cause a recrystallization even on the hardest portion of the shell, and yet is sufficient to relieve all internal strains and prevent the case from cracking in the mercuric-chloride test.

THE USE OF MERCURY SOLUTIONS FOR PREDICTING SEASON CRACKING IN BRASS.

BY HENRY S. RAWDON.[1]

The use of a solution of some salt of mercury as a means of detecting brass which is highly internally stressed and which may, as a consequence, develop season cracks later on, is well known and rather widely applied. In fact the use of some such solution for this purpose has been embodied in some specifications and instructions for inspection of material in which season cracking may be expected to occur. The New York Board of Water Supply Specifications (1915) require sheets and tubing less than $\frac{1}{4}$ in. in thickness to be "tested by immersion in a saturated solution of mercuric chloride for one hour and then kept under observation for two weeks." Material in which cracks develop is to be regarded as excessively stressed. The Ordnance Inspection Department (1917) specifies that cartridge cases must withstand an immersion of 4 hours in 1.5 per cent solution of mercuric chloride; International Aircraft Standards Board Specification 3N4 for Naval Brass or Equivalent Bars (1917–18) includes the following clause:

> "The rod shall stand an immersion in a mercurous-nitrate solution containing 100 g. of mercurous nitrate and 13 cc. of nitric acid (sp. gr. 1.42) for 15 minutes without cracking."

But little work, however, has been done to define this test or to point out its limitations. The present article summarizes the results of a series of examinations which were made in order to show what precautions should be observed in order to obtain concordant results in the use of this test as well as to show its limitations.

The prime requisite for the work was a series of samples which were identical with respect to the internal stresses which were set up in the material during the working of the metal.

---

[1] Associate Physicist, U. S. Bureau of Standards.

As material for the examinations, rods of manganese bronze 1 in. in diameter, which had been carefully investigated as to the distribution of stresses in any cross-section, were used.[1]

Although only one type of brass was used in the work, it is to be inferred from our general knowledge of season cracking and of the conditions under which it occurs that the conclusions reached are applicable, in a general way, to brasses of other compositions.

Some of the points which the work was planned to throw light upon are the following:

(*a*) The relative behavior of solutions of mercurous and mercuric salts;

(*b*) the relation between concentration of solution and the period of immersion necessary for the production of cracks;

(*c*) the effect of variations in the size of specimens used;

(*d*) and the possible influence of the character of the surface of the metal.

METHOD OF EXAMINATION.

Solutions of various concentrations of the two types of mercury salts were used, as shown in Table I. A saturated solution of mercuric chloride is approximately N/2, hence the use of solutions of this salt of a higher concentration than this is not possible. As stated above, cold-rolled manganese bronze in the form of rods 1 in. in diameter was the material used. Two rods were selected from material used by Merica and Woodward for the measurement of initial stresses in wrought brasses. The principal values given for the stresses in these specimens are summarized below:

Rod No.	Average Stress, lb. per sq. in.	Maximum Compression, lb. per sq. in.	Maximum Tension, lb. per sq. in.	Stress in Outer Layer, lb. per sq. in.
171	15 700	22 500	32 500	12 000 (tension)
173	37 500	53 500	65 500	40 000 (tension)

---

[1] *Technologic Paper No. 82*, Bureau of Standards, P. D. Merica and R. W. Woodward. The specimens used are referred to later by the number assigned to them in this pamphlet. Diagrams of the distribution of stresses are given in the publication, for the specimens used.

The approximate length of time required for cracks to occur upon immersion in a given solution was determined by periodically removing the specimen from the solution and rubbing off the precipitated mercury in order to disclose any cracks which might have formed. After this approximate period had been determined, other specimens were immersed in a fresh supply of the solution and allowed to remain undisturbed in the liquid for a period slightly shorter than that already determined. At the end of this time, one or two examinations were then usually sufficient to determine the time required for cracking, with some degree of accuracy. In some cases this period varied considerably even for adjacent specimens cut from the same rod and tested in the same solution, as shown in Table I. A rather large volume of solution, in comparison with the specimen, should be used, on account of the change of composition which occurs due to the precipitation of the mercury. The general rule of allowing approximately one liter of solution to each specimen was followed throughout; in those cases in which the action continued for a considerable length of time the solution was renewed at intervals during the period the specimen was immersed. A neat and rather accurate "indicator" of the "end point" was noted in the use of mercurous solution which had been acidified with nitric acid (Tables II and III). At the time the cracks, which in both the rods used were longitudinal radial ones, form, tiny bubbles of gas were noticed to collect on the specimen. These bubbles were arranged in straight lines along the length of the rod or radially on the cut ends, and upon examination the lines of bubbles were found to mark the course of the cracks. By making use of the appearance of these bubbles as an indicator, the time required for cracking for some specimens was fixed rather accurately, in some cases, periods as short as 20 and 35 seconds were determined.

RESULTS: CONDITIONS INFLUENCING THE RESULTS OF THE TEST.

Relation between Concentration of Solution and Time Required for Cracking.—A series of specimens 2½ in. long were cut from a rod of manganese bronze (No. 171) and the time required to cause them to crack was determined in solutions of mercurous nitrate and of mercuric chloride. The concentrations of the solutions varied from N/80 to N/2 as shown in Table I.

The results obtained indicate that mercurous salts are considerably more active than those of the mercuric series of the same concentration of mercury. This is best shown in Fig. 1, in which the logarithm of the concentration is plotted against the requisite number of minutes to produce cracking. By using the logarithm of the concentration rather than the concentration itself the curve is simplified considerably and rectified for the greater portion of its length.

TABLE I.—IMMERSION PERIOD REQUIRED FOR MERCUROUS AND MERCURIC SOLUTIONS OF DIFFERENT CONCENTRATIONS.

THE SPECIMENS, 2½ IN. IN LENGTH, WERE CUT FROM MANGANESE BRONZE ROD NO. 171.

Mercurous Nitrate ($HgNO_3$).			Mercuric Chloride ($HgCl_2$).		
Concentration.	Grams of Mercury per Liter.	Time Required for Cracking, min.	Concentration.	Grams of Mercury per Liter.	Time Required for Cracking, min.
$\frac{N}{2}$	100	1, 2, 2, 3.	$\frac{N}{2}$	50	4, 5, 6, 6, 10, 10.
$\frac{N}{5}$	40	3, 4, 5, 5, 5.	$\frac{N}{5}$	20	12, 15, 17, 17, 17.
$\frac{N}{10}$	20	7, 7.5, 7.5, 7.5.	$\frac{N}{10}$	10	12.5, 15, 20, 20, 20.
$\frac{N}{20}$	10	7, 8, 9, 9.5, 10.	$\frac{N}{20}$	5	20, 20, 20, 20, 26.
$\frac{N}{40}$	5	10, 10, 10, 13.	$\frac{N}{40}$	2.5	25, 28.5, 29, 29.
$\frac{N}{80}$	2.5	24, 31, 36.	$\frac{N}{80}$	1.25	55, 55, 55.

The time required to crack a specimen in a solution of any particular concentration will of course be governed by the intensity and distribution of the stresses in such a specimen and will not necessarily be even approximately the same value as given above. It is to be expected nevertheless that mercuric solutions will always be found somewhat less severe than those of the mercurous series of corresponding concentration. Fig. 2 shows diagrammatically the average number and depth of the cracks produced in the specimens of Table I. This illustrates in another way the differences in the intensity of the action of the two salts.

Effect of Size of Specimen.—From the manganese bronze rod (No. 173) 1 in. diameter, specimen varying in length from $2\frac{1}{2}$ to $\frac{1}{32}$ in. were sawed. These were cut in the order given in Table II. The time required to crack the specimens in a rather concentrated solution of mercurous nitrate was then determined as before.

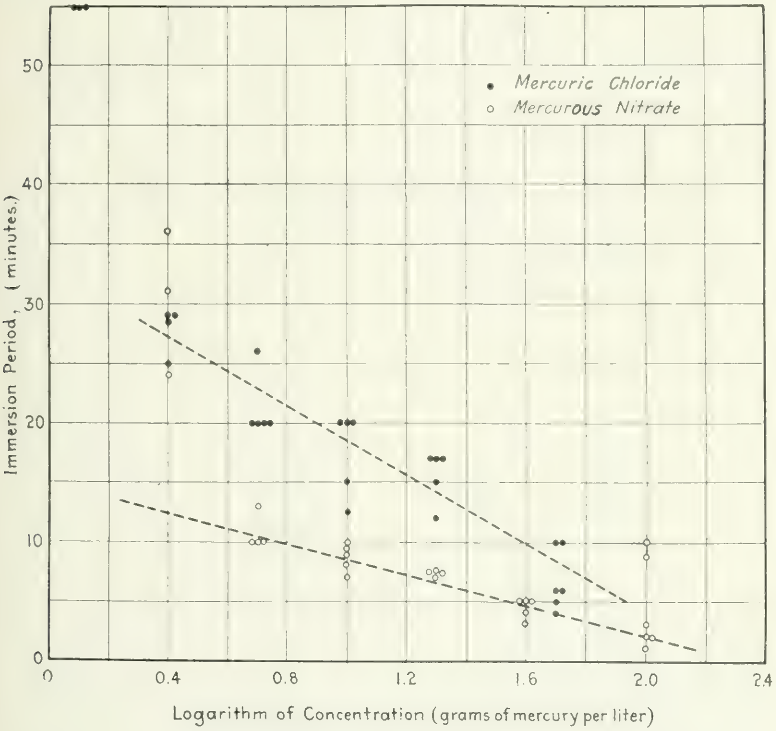


FIG. 1.—Relation between Immersion Period and Concentration of Solution for Rod No. 171.

The results indicate that for material of the kind used, that is, which season-cracks by splitting open longitudinally, the size of the specimen is a factor which need be given but little consideration. The results summarized in Table II also illustrate, incidentally, that cracks of this type are produced by those components of the internal stresses which are tangential and perpendicular to the length of the rod. Brass rods sometimes exhibit circumferential transverse season cracks. No material of this kind was available for study, but it is to be expected that in such cases the specimen must be of considerable size, as it is the longitudinal stress components, that is, those parallel to the length of the rod, which are instrumental here in producing the cracks.

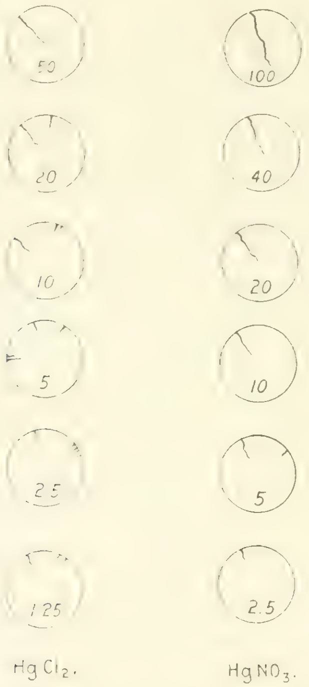


Fig. 2.—Typical Cracks produced by the Two Types of Mercury Solution of Different Concentrations. The numbers indicate the concentration of the solution in grams of mercury per liter.

In testing such articles as cartridge cases, it is customary to immerse the entire specimen. In the course of routine examination of such material it has been noticed that a longitudinal section of the case is usually sufficient for the test. If the case as a whole fails to pass the immersion test a longitudinal section will also usually fail. This applies particularly to specimens which develop circumferential cracks in the head and usually also for these showing the longitudinal ones, provided the section used constitutes 50 per cent or so of the case.

Influence of Character of the Surface.—The nature of the surface, particularly whether polished or not, is an important factor which determines the time required to produce cracks upon immersion. The results summarized in Table III on adjacent samples cut from the same rod illustrate this fact.

Two explanations may be offered to account for the influence the condition of the surface has upon the behavior of the specimen upon immersion: the flowing of the surface metal upon polishing may cover up fine furrows such as marks caused by imperfect dies, where cracking could most easily start; or the stresses in the outer skin may be relieved somewhat by the slight working of the surface metal. It was noted in most of the specimens used that the location of the cracks was determined by some surface imperfection, so that it is very probable that the first explanation is the correct one. The case noted by Mr. Webster (in this Discussion) of the cracking of brass rod and the ability of small parts cut from the same rod to satisfactorily stand the mercury test after the surface had

TABLE II.—INFLUENCE OF SIZE OF SPECIMEN.

MATERIAL.—MANGANESE BRONZE ROD, 1 IN. DIAMETER, NO. 173.
SOLUTION.—MERCUROUS NITRATE (100 G. PER LITER), ACIDIFIED WITH 13 CC. NITRIC ACID (SP. GR. 1.42).

Sample No.	Size, in.	Time Required for Cracking.
A	$2\frac{1}{2}$	20 seconds.
B	$2\frac{1}{2}$	1 minute.
C	1/[illegible]	1 minute.
D	$\frac{1}{8}$	3 minutes.
E	$\frac{1}{16}$	2 minutes.
F	$\frac{1}{24}$	1 minute.
G	$\frac{1}{32}$	$17\frac{1}{2}$ minutes.[a]
H	$\frac{1}{16}$	35 seconds.

[a] In smoothing off the roughness due to sawing, the convex edge was polished somewhat; this accounts for the longer period. (See Table III.)

been smoothed somewhat may be due to the same cause. Polishing of unsound material will delay cracking or perhaps even prevent it, so that if a very short period of immersion is specified, such material might satisfactorily pass the test. When cracks have once started, the action will continue for some time after the piece is removed from the solution, and it is very probable that specimens in which cracking has been delayed by polishing the surface, upon standing after being removed from the solution, may develop cracks. Not only should specimens which are being tested be examined for cracks produced during the specified immersion period but also after standing for some time after the material has been removed from the solution.

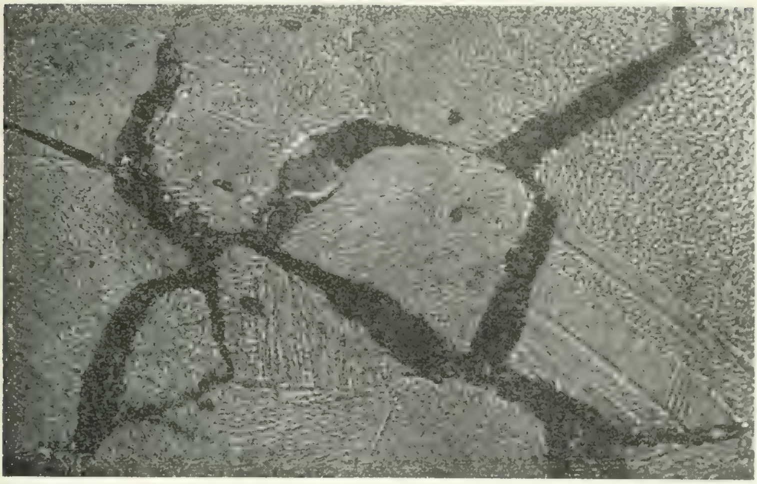
TABLE III.—INFLUENCE OF CHARACTER OF SURFACE OF SPECIMENS.

MATERIAL.—MANGANESE BRONZE ROD NO. 173.
SOLUTION.—MERCUROUS NITRATE (100 G. PER LITER) ACIDIFIED WITH 13 CC. NITRIC ACID (SP. GR. 1.42).

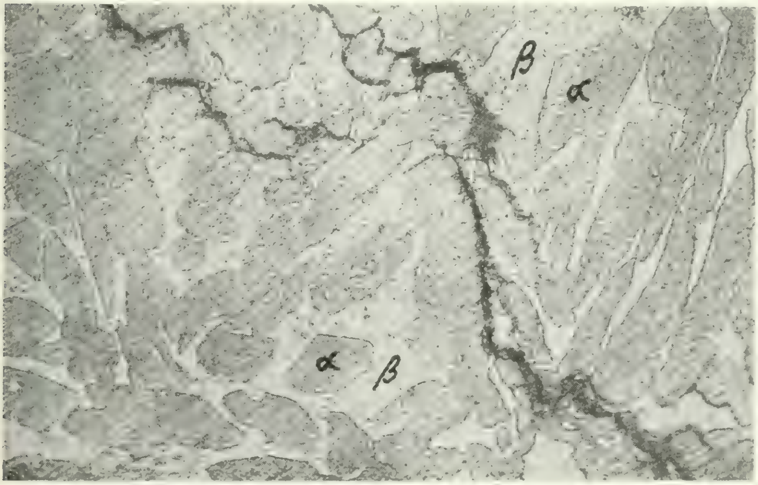
Sample No.	Size of Specimen, in.	Character of Surface.[a]	Time Required to Crack, min.
A	4	Surface was brightened with 00 French emery paper.	12½
B	3	Surface was brightened with 00 French emery paper.	18
C	⅜	Surface not polished.	4
D	⅛	Polished with 1 G emery paper.	31
E	⅛	Surface not polished.	4
F	¼	Polished with 1 G emery paper.	28
G	¼	Not polished.	5¼

[a] The surface referred to is the cylindrical one; the cut ends, resulting from sawing with a fine saw, were in all cases left in the condition resulting from the cutting.

Nature of the Action.—The microscopic examination of samples of brass which has "season-cracked" in some mercury solution throws some light upon the probable nature of the action of such solutions. Figs. 3 and 4 show the appearance of several such specimens. It will be noted that the cracks are intercrystallin; in cartridge brass, Fig. 3 (*a*), in which there are only the α crystals, the cracks are truly intercrystallin. In manganese bronze (60–40 brass) the cracks follow, in general, the boundary surfaces between the α and β constituents. In specimens, in which the action is relatively quite violent, particularly near the surface of the rod, the cracks may extend



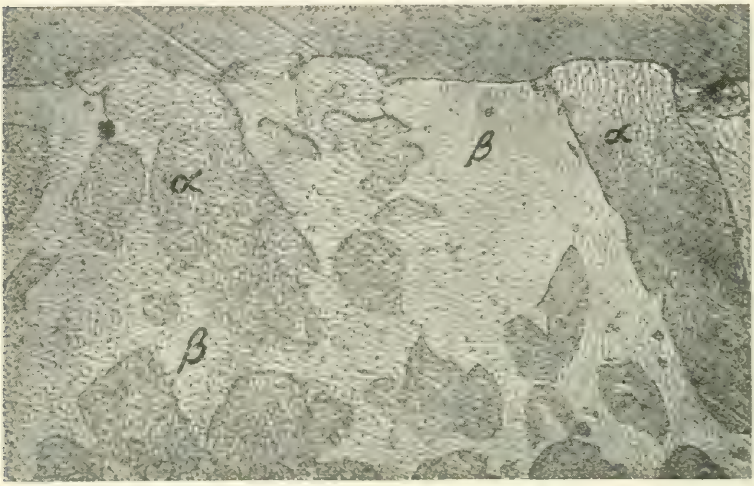
(*a*) 70–30 cartridge brass, cracked by using 1½-per-cent mercuric chloride for about 30 minutes. (×100.)



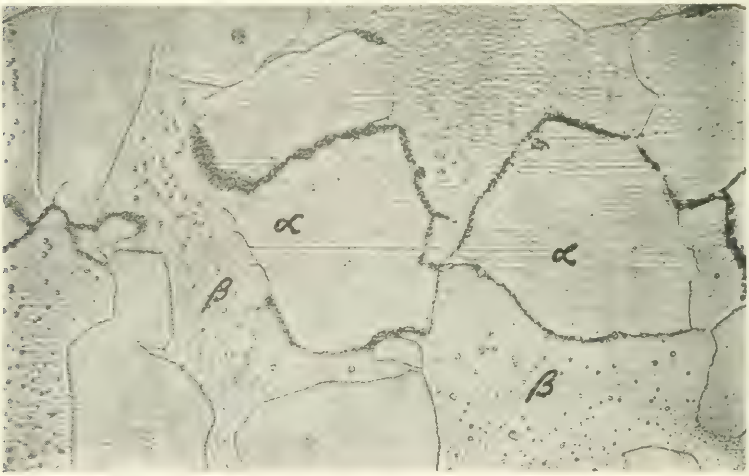
(*b*) Manganese bronze cracked by the use of mercuric chloride. (×500.)

FIG. 3.—Microstructure of Brass, "Season-cracked" by the Use of Mercury Solution.

Etching for both specimens: concentrated NH_4OH.



(*a*) Cross-section of a manganese bronze rod which has been immersed several hours in N/2 mercuric chloride solution; the upper edge, which is the surface of the rod, has been protected during polishing by a layer of electrolytic copper deposited upon it. The *α* crystals project considerably above the *β* due to the more rapid attack of the latter. (×500.)



(*b*) Manganese bronze which has been cracked by mercurous nitrate solution—the mercury was not volatilized from specimen before polishing and tiny drops of it have exuded out upon the surface of the *β* crystals. (×500.)

FIG. 4.—Microstructure of *α*-*β* Brass after Immersion in Mercury Solution. Etching for both specimens: concentrated NH_4OH.

across and through either of the two constituents as they are torn apart when the crack has once been started. Near the inner end of the crack the action is more gentle and the true method of attack is here clearly shown, as is illustrated by Fig. 3 (*b*).

The action is due, in all probability, to a solution of the mercury in the alloy. Soft annealed sheet copper, when thoroughly amalgamated with mercury, is very brittle and breaks with a rough intercrystallin fracture. The mercury may be easily volatilized by gently heating the specimen and the copper again shows its usual ductility.

The β constituent of α-β brass is more readily attacked by both types of mercury solutions than is the α. This is shown in Fig. 4 (*a*), which shows the edge of a cross-section of a specimen which has been immersed in mercuric chloride solution for several hours. The β matrix has been dissolved faster than the α crystals embedded in it, so that the α crystals stand out in relief above the general surface of the specimen. Similar material which has been attacked by the mercurous solution shows the same appearance at the surface.

All of the specimens shown in the micrographs referred to above were gently heated before the section was polished for microscopic examination, so as to volatilize the mercury. Fig. 4 (*b*) shows the appearance of a specimen which was not so heated. After polishing and etching, tiny globules were observed under the microscope to form on the surface of the β constituent. These are undoubtedly tiny drops of mercury which exude from the alloy. Very few spots of this kind were found on any of the α crystals. All of the immersion tests were carried out at room temperature. A careful regulation of the temperature appears to be unnecessary in view of the fact that quantitative results are more or less approximate even at the best.

SUMMARY.

Solutions of the mercurous series of salts are considerably more active than solutions of the mercuric series in promoting the cracking of highly stressed brass of the 60–40 type.

The difference in action is due in all probability to the different state of the mercury in the two solutions, the monova-

lent and divalent state, respectively. In the rods used, the action of the mercurous solution is, in general, localized in producing one deep crack; the mercuric solutions cause the specimen to crack in several places. None of these cracks are as deep and wide as the single one of the first case.

The size of the specimen was found to be a negligible factor for the material used, that is, material in which the stresses producing the cracks lie in the plane of the cuts made in sampling the piece. In other types of material the size of piece must be given consideration.

The character of the surface is a factor of considerable importance in determining the immersion-period required to produce cracking. Simple polishing of the surface was sufficient to increase this period in the ratio of 1 to 6 or to 7. This is probably due to the imperfections of the surface being covered over, at least partially, by the slight surface flow of the metal. Specimens which are required to stand a specified period of immersion should be examined after they have stood for some time after being removed from the solution as well as when first taken out.

The fractures produced are of the intercrystallin type; the mercury which is precipitated from the solution is taken up by the alloy, particularly by the β constituent. The dissolved mercury reduces the cohesion between adjacent crystals sufficiently so that the intercrystallin type of fracture results.

DISCUSSION.

Messrs. Flinn and Jonson.

MR. ALFRED D. FLINN AND MR. ERNST JONSON (*presented in written form*).—Hydrostatic pressure tests upon brass (manganese bronze) cylinders were made during the past three years by the Board of Water Supply of the City of New York, under the direction of Chief Engineer J. Waldo Smith. They indicate that the previous conclusions with regard to initial stress in brass were correct, to wit: that when the stress is not excessive the metal, if correctly made and not abused in fabrication of the article used, is reliable and will stand continuously applied stress for an indefinite period. The "stress," when considered in designing, must include all stresses to which the metal is simultaneously subjected at any time,—"initial" stress, "working" stress, "temperature" stress and any others. Unless, however, absolute proof can be had that each and every piece is free from initial stress, or a safe allowance for initial stress can be made, alloys of this type should not be used in places where failure would have serious consequences.

Nine cast manganese-bronze cylinders 24 in. long were provided, three each of 10, 18, and 40-in. inside diameter, with walls $\frac{3}{4}$ in. thick. They were very carefully made to secure accuracy of dimensions and sound castings. No machining was done except on the ends, where joints were formed for purposes of the tests. Two of the 40-in. cylinders had slight foundry imperfections, which were repaired by burning in. In the tests each set of three cylinders of the same diameter were assembled end to end vertically, between the heads of the testing machine and all cylinders of the set were subjected to the same pressure. Tests of the 10 and 18-in. cylinders were begun January 21, 1916, and of the 40-in. cylinders August 20, 1917. Pressures were maintained within a small range by means of a pump operated by an automatically controlled electric motor, and an accumulator. The pressures applied in the 10 and 18-in. cylinders were about 1100 lb. per sq. in. (jumping to 1450 for a minute, when the pump operated, falling to normal in about 8 minutes, upon the

Messrs. Flinn and Jonson. stopping of the pump), pressure being maintained continuously night and day for long periods, excepting accidental, comparatively brief interruptions. The corresponding tensile stresses in the metal were approximately:

Inside Diameter of Cylinders, in.	Tensile Stress, lb. per sq. in., at Unit Hydrostatic Pressures of:			
	800	1000	1100	1450
10			7 300	9 600
18			13 200	17 400
40	21 300	26 700		

One 18-in. cylinder had a porous spot about 1½ in. in diameter, which was made tight by peening, and so remained until July 28, 1916, when a crack opened to a width of about $\frac{1}{32}$ in. This crack was again peened tight and so continued.

On October 5, 1917, a 2-in. longitudinal crack appeared in one of the 40-in. cylinders, along the edge of a burn. After several unsuccessful attempts to close this crack by peening and soldering, it was peened tight. It did not so stay, however, but gradually extended to 8 in., its length agreeing with that of the burn. This cylinder was therefore discarded. Great difficulty had been experienced in making such large castings with such thin walls. The burning-in was done by treating the cylinders locally to a high temperature and then pouring molten metal into the place to be repaired. The cylinders were not annealed after burning. The fact that this 40-in. cylinder did not crack until it had been under pressure for 1½ months, and then cracked the full length of the burn, seems to indicate that the crack was due to stress, but that the stress due to the cooling of the burn was not sufficient to cause it.

On November 1, 1917, the two remaining 40-in. cylinders were reassembled and a pressure close to 1000 lb. per sq. in. maintained until November 30, 1917, when a small crack developed along one edge of a burn. No attempt at repairs was made. In February, 1918, tests on the 40-in. cylinders were discontinued. The two cylinders had been distorted to a

Messrs. Flinn and Jonson.

slightly barrel-like shape, with the middle diameter about ½ in. greater than the end diameters. All tests were discontinued at this time. The burning-in had been done in a manner which had hitherto been considered good practice. The fact that cracks occurred around these burns indicates that even when all the known precautions have been taken, a burn causes cooling stresses which weaken the metal.

Another test is of interest. Near the Ashokan reservoir, New York, eight rods ¾ in. in diameter and about 8 in. long, threaded at both ends, have been subjected continuously to a working stress of 16,000 lb. per sq. in. since June 25, 1915, being all the time fully exposed to the weather and to its tarnishing effect. These rods have shown neither cracks nor other signs of failure. This is further confirmation of the conclusion stated in the first paragraph of this discussion. The working stress in each case was applied in the form of a dead load of approximately 8000 lb. consisting of stone and a wooden containing tray suspended from the lower end of the rod by means of a suitable device. The axis of each rod is vertical and its upper end is supported by a strong wooden tripod. There is one rod each of the following kinds of metal, all hot-worked: Muntz metal, gun metal (88 copper, 10 tin, 2 zinc), Naval brass, Spare's manganese bronze (extruded), Monel metal, aluminum bronze (Titanium Alloys Mfg. Co.), Spare's manganese bronze (drawn), Spare's cast manganese bronze.

Because of the tediousness of determining accurately the yield point of brass by the method now used, and the unreliability of results if tests by the present method are made rapidly, it is suggested that there be devised a new form of test requiring little time and utilizing the column principle or some other, which can be applied accurately and which will give better results. The revised concept of brass which has resulted from recent experience requires an accurate and quick determination of the yield point. It appears now that the working strength of brass and other copper alloys has little or nothing to do with the ultimate strength or with elongations, as formerly determined by use of "standard" test specimens, but that the two important facts that should be known about all such alloys are the yield point, and the initial stress introduced into the metal by pro-

Messrs. Flinn and Jonson.

cesses of manufacture and fabrication. The strength available for working purposes is the difference between the yield point and the initial stress.[1]

Although, as stated, the strength available is the difference between the yield point and the initial stress, it is not intended to convey the idea that the metal could ordinarily be stressed for engineering purposes up to the yield point, but rather that it would be better practice to apply a factor of safety to the yield point instead of to the ultimate strength, this factor, of course, to be selected in accordance with the purpose for which the metal is to be used in any case. Dr. P. D. Merica's experiments, as recorded in Technologic Papers of the Bureau of Standards, seem to confirm the writers' determination of the yield point for manganese bronze at about 27,000 to 30,000 lb. per sq. in. His value of 25,000 lb. for the limit of stress beyond which the material will invariably "season crack" is taken as equivalent to an independent determination of the yield point by a different method. Owing to the difficulty in determining the yield point of such material closely, and the wide variation in strength of such alloys as made by different manufacturers, it is not strange that there should be differences even as high as 5000 lb. in yield point determinations; ultimate strengths vary several times as much.

A column test for determination of the yield point might be developed which could be applied by a simple testing machine. The fittings for making this proposed test would be a self-centering end bearing block with a knife-edge bearing or a ball-and-socket bearing, to insure axial application of the load. In the case of rods, of any uniform cross-section, all that would be necessary then would be to cut off a piece about ten diameters in length, taking care to have both ends plane and perpendicular to the axis, within reasonable accuracy for machine-shop work.

Warning is again sounded against excessive claims still made in some quarters for physical characteristics of some of the copper alloys. As formerly, these claims appear to be based upon results of tests made by methods designed for steels

---

[1] In the outer layers of some specimens the Bureau of Standards has found initial stress even greater than the average *breaking* strength of the metal.

Messrs. Flinn and Jonson.

and not suitable for revealing the true capacities for engineering uses of the brasses offered for such uses. Until more is known about certain details of production and use of these metals, and more certain methods of inspection and testing shall have been put into practice, engineers must adopt them with caution. Such test results as are recorded above, and in the discussion of Mr. R. C. Becker, prove that these alloys have possibilities. But would-be users of manganese bronze and similar cuprous alloys for engineering purposes are again reminded of its limitations, as brought out in papers and discussions before this and other societies and in the Technologic Papers of the Bureau of Standards. The claims of parity with steel—the high tensile strength and other physical qualities as shown by tests of a type designed for steel—are misleading.

Since the Board of Water Supply, owing to the completion of the greater part of its work and to the war, has no longer either the technical staff or the facilities for continuing investigations of bronze begun and inspired by its engineers as a result of their unusual experiences, these investigations must be pursued by the Bureau of Standards and the manufacturers, who have a continuing interest in them.

Mr. de Forest.

MR. A. V. DE FOREST.—I have been greatly interested in Mr. Price's cure for the generally unstable state of brass artillery cases. As ordinarily made these are either so hard as to be liable to corrosion cracking, or so soft as to swell and stick in the gun. As this is a fatal objection, the cases are made as soft as may be without sticking, but are thereby always left with very considerable internal stresses. The magnitude which these stresses may assume without causing trouble is indeterminate, inasmuch as we have no corrosion crack test which is of much more than qualitative value, and no way of correlating these tests to the conditions of actual practice. These are in themselves perfectly indefinite, for conditions will vary from the ammonia fumes of a manure heap which will rot even annealed brass, to a dry atmosphere in which a well-varnished case will last indefinitely even with high tensile strains at the surface of the brass.

In consequence of Professor Heyn's remarks, quoted by Mr. Price, I conducted a series of tests on the same general

Mr. de Forest. subject of low temperature annealing. As my results in a narrower field led to opposite conclusions from those of Mr. Price, they may be of some interest.

A little experience with artillery cases showed such variation in individual specimens that no conclusions could be drawn without very extensive experiments. My observations were made on hard-rolled sheet metal and therefore are restricted to that field. Hard-rolled 70–30 cartridge brass of about 40-per-cent reduction was cut into strips ½ in. wide and 0.140 in. thick, with milled edges. Strips from the same sheet were used. The surface was cleaned with No. 0 French emery paper. Mercuric chloride and nitrate were rejected for their irregular action and the difficulty of seeing small cracks produced by them. The specimens were compared as to stress conditions by placing them together for 12 hours in a dessicator which had concentrated ammonia in the bottom. The surface tarnish was then etched off with dilute nitric acid, leaving a surface in which the structure could be seen under the microscope, and the specimen was examined at a magnification of 66 diameters. The cracks were then very distinct even when invisible to the naked eye.

The tendency to crack seemed to vary even in the same piece of brass, and indentations were made in each piece in order to give the crack, as it were, a place to start, in an attempt to produce similar conditions in the different samples. The indentations from the 500-kg. Brinell machine were used, and it was also found that the slight mark left by the scleroscope hammer produced the same effect to a less marked degree. This latter shows how easily this test may be made useless by accidental conditions.

Specimens heated at 218° C. in naphtalene vapor for 1, 9.5, 19, 28.5, 38 and 48 hours all showed cracking. Those at 9.5 and 38 hours were worst, those at 48, 28.5 and 19 hours and unannealed following about in order. There seems a leaning, more or less well marked, toward a greater tendency to crack after this heat treatment than before.

At 243° C., tests were tried for 1, 3.8 and 10 hours. All showed slight cracks in the untouched metal and marked cracking at the dents. At 250° C. there was cracking at Brinell

Mr. de Forest. dents and slight cracks in the original metal after 13 hours. No transformation was seen at 500 magnification.

Short heatings of two minutes were tried. Here the specimens, about 2 in. long and ½ and 0.140 in. thick, were suspended in molten sodium and potassium nitrates at the following temperatures, and vigorously stirred. The bath was so large that it did not measurably change temperature when the cold specimen was immersed:

TEMPERATURE.	REMARKS.
454° C....	No crack. Complete transformation with very small grain size.
347° C....	No crack. Partial transformation, about one-fourth of the field showing crystal break up at 500 magnification.
297° C....	Wide cracks. No transformation.
272° C....	" " " "
254° C....	" " " "
100° C....	" " " "
Cold......	" " " "

Contrary to expectation, it then appeared that there was in this material no marked reduction of internal stress until transformation had proceeded so far as to be visible under the microscope at 500 magnification.

Tests were then made in a cruder, but more conclusive way. Strips of hard-rolled stock were annealed at one end and left hard at the other. Careful examination, particularly of the polished and etched longitudinal section, showed that the cracks stopped more or less abruptly at the beginning of visible transformation. Similar tests on wire of different degrees of hardness seem to support the same view. This examination also showed that the cracks, whether large or small, penetrated about one-third of the thickness of the sheet metal. Slight bending showed that the end of the crack could be seen at the magnification used, and did not continue through. If the metal was broken the appearance of the fracture showed the extent of the crack due to ammonia. The period of annealing was varied up to several hours in this test without changing the result.

It also seemed of interest to study the hardness and the strength of this brass after low temperature annealing of one

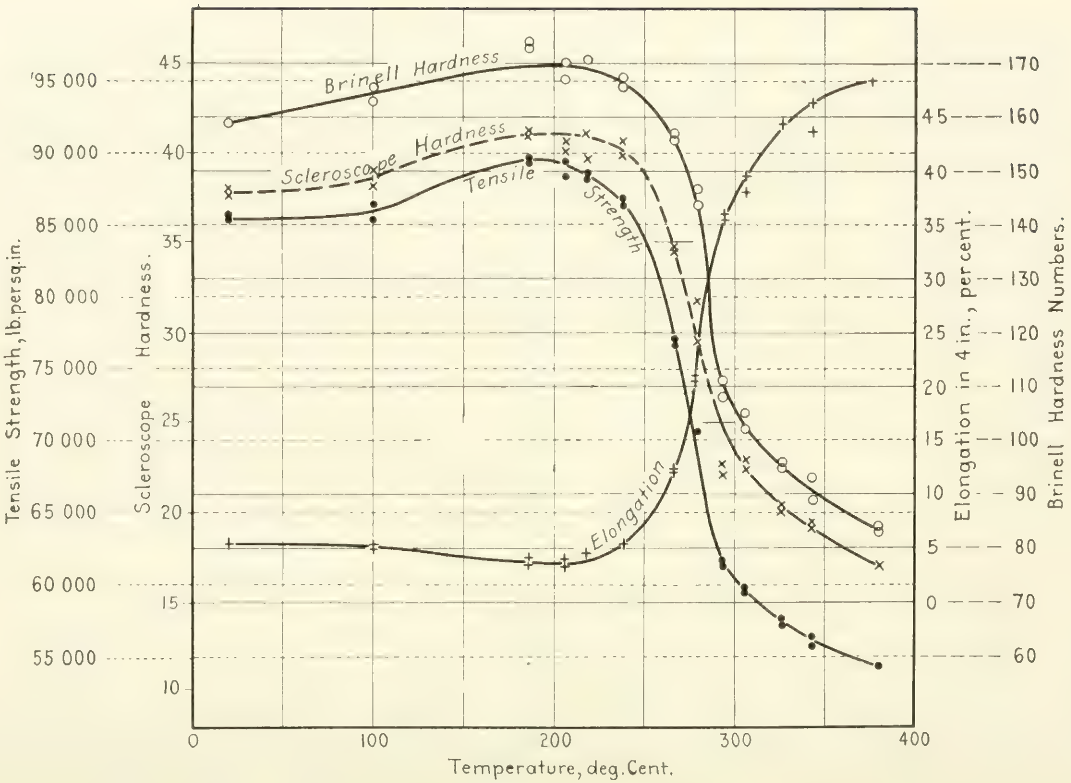


FIG. 1.—Curve Showing Changes Due to Low Temperature Annealing' 70/30 Brass, 40 per cent Reduction. 1 Hour Anneal in Each Case.

Mr. de Forest. hour duration. The test specimens were ½ in. wide at the central portion, ¾ in. at the grips, 4 in. in length over which elongation was figured, and 10 in. long over all. The results are plotted in Fig. 1. They show clearly the hardening due to low temperature treatment. Careful search did not show transformation at a lower temperature than 266° C., but signs of change were noticed here. At this temperature all the physical properties measured had markedly changed. At 279° C. the transformation was well marked.

These tests seem to indicate that as cartridge brass of about 40-per-cent reduction is annealed at progressively higher temperatures, the first effect is a hardening one, with a maximum at about 200° C., followed by a softening which can be detected by measurement of any of the usual physical properties before it can be noticed under the microscope, and before the internal stresses are markedly relieved. It may be that the above order is reversed in the case of other reductions and other alloys. The exact conditions governing these matters remain to be studied.

I may venture to suggest that the protective results obtained by Mr. Price may be due to undetected softening of the heavily worked sections with the resulting reduction of internal stresses, rather than to a relief of stress without other physical change.

Mr. Price. MR. W. B. PRICE.—I am not surprised that Mr. de Forest obtained results on hard-rolled 70-30 artillery brass reduced 40 per cent which led to opposite conclusions from those based upon my tests on artillery cases, for the following reasons:

First, the conditions of the two sets of experiments were entirely different. In hard-rolled sheet metal the stresses are of a compressive nature, whereas in drawing artillery cases the material strains are caused by tension.

Second, the action of ammonia on brass under internal strains is entirely different from that produced by mercuric chloride. Ammonia is much more corrosive and destructive in its action. It will cause cracking in brass that is under only slight stresses, and will even rot annealed brass, as stated by Mr. de Forest. This is not the case with mercuric chloride.

Third, the reductions in the case of the hard-rolled brass were 40 per cent, while in the artillery cases the maximum reduc-

Mr. Price. tion at the mouth varied from 18 to 20 per cent. This difference in reduction would account for the different hardening and transformation temperatures obtained by Mr. de Forest and myself.

These apparent inconsistencies only emphasize the great necessity for a rapid, reliable, commercial test for the detection of corrosion cracking.

I cannot agree with Mr. de Forest that the protective results obtained were due to undetected softening of the sections A, B, C, D and E taken according to the U. S. Government specifications, with the resulting reduction of the internal stress. This is proved by the physical tests. His statement would hold true in the heavily worked sections, such as the flange, and that is so stated in the paper. Whether this heat treatment has entirely relieved all internal strains or only diminished them to a certain degree can only be left to the future, when instruments delicate enough to test this point have been devised. The strains were nevertheless relieved to a sufficient extent to pass the government mercuric-chloride test, without affecting the physical properties, as measured by the ordinary testing machine.

In talking over my paper with Mr. de Forest, he stated that the impression might be created that brass could be worked under all conditions to the limit of commercial reduction and then made free from corrosion cracking simply by a special heat treatment. Such a heat treatment would not be commercially feasible, and I should be the last person to advocate special heat treatment as a cure-all. It seems to me, however, that the title of my paper indicates clearly that this treatment applies only to a special condition with which I was confronted and for which a specific remedy was found.

Mr. Smith. MR. F. G. SMITH.—Mr. de Forest speaks of the work that should be done on the reduction of brass before annealing, and its relation to corrosion cracking.

A start has been made by determining the Brinell hardness of annealed brass after different reductions. It has been found that if the reduction is very severe, annealing before the point where recrystallization begins causes the brass to harden, and if the reduction before annealing is comparatively light, the hardness falls off before recrystallization begins.

There may possibly be some difference in the effects of annealing at temperatures below the recrystallization point in order to prevent cracking, depending on the reduction given the brass before such annealing. **Mr. Smith.**

MR. C. H. MATHEWSON.—Mr. Bassett has brought out the fact that the cracks occurred between the crystals. That is also brought out in Mr. Rawdon's paper. It suggests, of course, that any impurity in brass, which is of an intercrystallin nature and which is specifically weak or brittle, —I presume lead might be included in this category and I think from investigations which I have made that cadmium may also be included, certainly where appreciable quantities of cadmium occur in the brass,—would naturally incline to favor season cracking, particularly if such an impurity were easily corroded under atmospheric conditions. This is merely a generalization and of course you cannot settle matters of detail from generalizations. Such generalizations are open to qualification, and particularly in the case of impurities, to qualification dealing with questions of the solid solubility of these impurities. It is possible to conceive of an impurity which when present at 0.2 per cent, for example, is intercrystallin, easily corroded, weak and brittle, and under such conditions I can hardly imagine anything but an increased tendency towards season cracking as the result. On the other hand, a smaller amount of this impurity might easily occur in solid solution and bring about entirely different conditions. **Mr. Mathewson.**

It seems to me that the merits of the situation with respect to the several common impurities which occur in brasses have not yet been revealed. The difficulty there, as I see it, is the difficulty in making accurate and careful comparative tests; that is to say, corrosion cracking is now tested in a more or less unsatisfactory manner. If we were able to make simple tests of this property, comparable with the ordinary tension test or with a great many other physical or chemical tests, we could easily settle many of these questions as to the effect of small amounts of impurities. At present, the simplest expedient is to draw or over-draw the object, leave it for a seasoning test and observe the results. It seems to me that under those conditions, it is necessary to test a very large number of objects in order to arrive at any very conclusive results. The only criti-

Mr. Mathewson. cism, and that is perhaps a trifling one, of the tests given in Mr. Bassett's paper, is that not enough shells were used. The results would have been more conclusive if 50 or 60, instead of 15, had been used.

The Chairman. THE CHAIRMAN (MR. W. H. BASSETT).—Replying to Mr. Mathewson, I should like to say that these tests were taken up recently and more work is being done in the same direction. It is understood that several investigators are studying this question and we shall undoubtedly have further discussion of the results later on. Our results are offered simply to show what the work has thus far indicated. As Mr. Mathewson suggests, it may be well to await the results of further investigations before coming to a final conclusion.

Mr. Schramm. MR. EDWARD SCHRAMM.—It has been demonstrated that cadmium very rarely occurs in ordinary commercial brass in amounts exceeding 0.02 per cent. The conditions in Mr. Bassett's experiments, in which considerable quantities of cadmium were purposely added, were, therefore, far more adverse than those of actual practice. These experiments having shown the lack of any connection between corrosion cracking and cadmium content, little remains of the assertion that cadmium is responsible for the failures by season cracking which have appeared in practice.

Mr. Breyer. MR. F. G. BREYER.—Mr. Bassett's paper is offered as data on the question of whether or not the cadmium impurity carried by zinc distilled from Western ores and the freedom from this element of the zinc distilled from New Jersey ore, is a possible cause for increased liability to season cracking of brass. The evidence given in this paper seems to indicate that cadmium, added to New Jersey metal, does not increase season cracking. It should be borne in mind, however, that while cadmium has been commonly picked out as the chief difference between Western low-lead spelter and New Jersey metal, this is not the only characteristic difference between these two materials. We know that the Western ores generally carry appreciable quantities of arsenic, indium, gallium and germanium, and we know that these are common constituents of the metal distilled from these ores. The great difference in hardness, as measured by the ring between the Western and New Jersey metal, may be

Mr. Breyer.

due to the presence of these rare elements. This difference in hardness or ring to the hammer is unmistakable to anyone who has handled spelter in any variety.

It would seem, therefore, that while Mr. Bassett's paper offers some good evidence on the question of cadmium, it does not entirely answer the question. Is there a difference in the tendency to season cracking of brass made from Western metal as against New Jersey metal? It is fair to say that Mr. Bassett has not indicated himself that his paper answers the question, and it is only for fear that some one might gather this impression from a hasty reading that these remarks are offered.

There is a very important factor that should be mentioned here in connection with this difference in metal and that is, that the New Jersey ore has run for years, and mine samples show that it will continue to run for years to come, of the same uniform composition. The purity of the metal made from this ore is not dependent upon the last refinement in plant control, but was determined when the material was laid down in the ground.

In the case of the Western metals, with the exception of small lots of ore here and there, the process of securing pure metal is largely that of human control, and, while this control has been developed to a high state in certain cases, the human element is there and the question of uniformity and certainty of product cannot be guaranteed. From personal knowledge, I can say that I have seen tens of thousands of analyses of metal from the New Jersey ore with less than a few hundredths variation in the percentage of impurities.

The Chairman.

THE CHAIRMAN.—The statement in regard to cadmium in my contribution to this Topical Discussion was brought to attention because of numerous suggestions that season cracking was caused by a small percentage of cadmium which brass contained. These suggestions, without proof or investigation, are likely to be misleading, as neither experience or such investigations as have been thus far made indicate that cadmium has any influence in bringing about such trouble. We recognize that there may be other impurities besides cadmium in zinc, and, of course, copper contains small amounts of impurities also. We are not in a position to settle the effect of all of these impurities.

Mr. Becker.

MR. R. C. BECKER (*by letter*).—In the spring of 1915 it was discovered that many of the large manganese-bronze castings

Mr. Becker. installed in the valve chambers of New York City's Catskill Aqueduct were developing season cracks. All of these castings had been subjected to a shop acceptance test of 200 lb. per sq. in., maintained for a period of at least a half-hour, and they had appeared to be satisfactory. A careful examination showed that the cracks were in every case in the vicinity of a repair made at the foundry by the burning-in process.

It was decided to subject some of these castings, already installed in one of the valve chambers, to a prolonged hydrostatic test before putting them into service. A chamber was selected which contained six manganese-bronze castings, consisting of two 30 by 30 by 48-in. manganese-bronze tees each weighing about 10,000 lb., to the outlets of each of which were bolted two 30-in. manganese-bronze gate valves each weighing approximately 8800 lb. One tee and its two valves were kept under close observation but no pressure was applied; the other tee and its two valves were placed under a hydrostatic pressure of 250 lb. per sq. in., which was maintained by an automatic pumping arrangement. The pressure was applied on April 22, 1915, and maintained with a few interruptions until September 28, 1916; the maximum fluctuation in pressure did not exceed 12 lb. per sq. in.

The bronze tee under test and the one under observation were free from burns and showed no signs of cracking or other weakness. The four 30-in. valves contained burned-in patches in both their bodies and bonnets. The behavior of these four valves may be briefly stated as follows:

The southerly valve of the two under the pressure of 250 lb. per sq. in., showed no defects until May 3, 1915, when a small crack about $\frac{1}{8}$ in. long was discovered in the bonnet, followed, on May 26, 1915, by another crack $\frac{1}{2}$ in. long near the first one. After a short time leakage from the cracks stopped and they could not be found. The pressure was released October 25, 1915, and when again applied on November 9, 1915, the cracks became quite evident and leaked freely. An examination of the interior of this bonnet during March, 1916, showed a long crack, open about 0.008 in., running along the upper edge of a burned-in patch. No further cracking or extension of the existing cracks was observed in this valve up to September 28, 1916, when the test was discontinued.

Mr. Becker.

The northerly valve under pressure showed no leaks until September, 1915, when leakage from two small cracks was discovered in the bonnet. When the casting was jarred with a hammer the leakage ceased and the cracks could not be found even after the surface of the metal had been carefully scraped. The pressure was released on October 25, 1915, and again applied on November 9, 1915. The above-mentioned leaks reappeared with the reapplication of the pressure and from November 15, 1915, to November 26, 1915, this valve bonnet cracked very extensively. One of the cracks developed to a length of 5 in. running horizontally, in the center of the bonnet. The other crack branched and developed to an extreme length of 8 in. running about 7 in. above the bonnet flange. An examination of the interior of the valve showed the cracking to be more extensive there than on the outside, the cracks being open about 0.004 in. No further cracking or development of existing cracks was noticed between November 26, 1915, and September 28, 1916, when the test was completed.

A crack developed in one of the two valves under observation but not under pressure during January, 1916. This crack, about $1\frac{1}{2}$ in. long, was in the body of the valve just above a burned-in patch. No further cracking has since been observed. In June, 1915, the bonnet of the other valve appeared to be slightly cracked, but the crack could only be definitely recognized as such, by the fact that after the metal had been chipped in the direction of the crack, the chip split into two pieces along the apparent line of the crack. By January, 1916, the crack which had been barely visible in June was about 10 in. long, and open wide enough to take the thin edge of a knife. Another crack on the opposite side of the same face developed to a length of 6 in. After January, 1916, very little change took place in this valve. It may be noted that these valves and tees were installed in an underground chamber so that the temperature variations probably did not exceed 10° F.

Soon after the above test was started two of the worst cracked 30-in. manganese-bronze valves were removed to a testing shed and bolted to a perfectly sound 30 by 30 by 48-in. manganese-bronze tee. One valve had a horizontal crack 8 in. long open about 0.03 in., near the center of one face

Mr. Becker. of the bonnet. On the opposite face there was another crack extending about 5 in. vertically upward from the flange. The body of this valve had a bad crack about 8 in. long extending around the corner between the side and face of the valve. All of these cracks were in the vicinity of burned-in patches. To make the valves tight enough for testing purposes patches of pure gum rubber were cemented over the cracks on the inside of the valve. These rubber patches effectively cut off the leakage without adding anything to the strength of the valve. The other valve had a perfect bonnet, but had many burned-in patches in the groins between body and outlets and several ill-defined cracks had developed in the vicinity of these patches.

The intention in testing these two valves and the tee was to "treat 'em rough." A hydrostatic test was started in August, 1915, at a pressure of 200 lb. per sq. in., and this pressure was increased by stages until 480 lb. per sq. in. was reached in February, 1916. Under these pressures the large cracks in the bonnet and body of the first valve did not increase at all. Two smaller cracks not much over 1 in. in length appeared in the bonnet of this valve during November, 1915, but showed no signs of lengthening.

In April, 1916, the valves were unbolted from the tee and an attempt was made on one of them to cut out the defective and cracked metal and then fill up the holes by oxy-acetylene welding. The welds proved to be porous, probably due to the fact that the metal in the original casting was so dirty that a good weld was impossible. Moreover, the casting was pretty badly distorted by the welding even though it had been preheated before welding. After welding, this valve was subjected to pressures up to 520 lb. per sq. in., when the weld failed. Both valves were then shipped to the Rochester Welding Works where another attempt was made at welding them by the oxy-acetylene method. The castings were preheated to 740° F., and after welding were packed in asbestos and left to cool, which took several days. After welding the castings were quite distorted.

Each valve was again subjected to a very severe hydrostatic test. The valve which had been rewelded showed leakage

Mr. Becker.

through the welds at low pressure, but by peening shut the places where leakage occurred the pressure was finally raised to 680 lb. per sq. in. After about 36 hours a large tear about 10 in. long appeared in the lower part of the valve and the test on this valve was discontinued. The other valve was then set up and the pressure run up quickly to 650 lb. per sq. in. The welds proved to be fairly tight, showing only a slight ooze at one or two points. The valve was then drained and allowed to stand from November, 1916, until April, 1917. During this time it was subjected to some very low temperatures (0° F.).

In April, 1917, the pressure was rapidly run up to 700 lb. per sq. in. without any signs of failure. The pressure was maintained at from 700 to 800 lb. per sq. in. for four days. The leakage at the flanged joints during this time was equal to the pump capacity at these pressures. Next the bonnets of the two valves were bolted together and the pressures run up to from 900 to 970 lb. per sq. in. Under these pressures the welded bonnet showed only a very slight ooze and in other respects the bonnets showed absolutely no signs of failure. It may be stated that both valves and bonnets were pounded with a 20-lb. sledge hammer while under high pressure without any apparent damage to the castings.

An attempt was made to break the large manganese-bronze tee to which the 30-in. bronze valves were bolted in the early part of the experiment. From October, 1915, to April, 1916, the pressure was raised in stages up to 400 lb. per sq. in. From April to July, 1916, the casting was subjected to pressures ranging from 600 to 880 lb. per sq. in. This casting received a great deal of abuse, these high pressures being released to zero in less than 10 seconds and again built up to 700 or 800 lb. per sq. in. within a few minutes, and this was repeated dozens of times. While under these high pressures the entire surface of the casting was pounded as hard as possible with a 20-lb. sledge. Finally under a pressure of 880 lb. per sq. in. we succeeded in producing a crack about 15 in. long in the dome covering the tee and cracks on the inside on the center line of the groins between the body of the casting and the outlets. None of these cracks, however, extended clear through the metal. Of course, a great deal of leakage occurred at the flanged joints,

Mr. Becker. and owing to the fact that the $1\frac{1}{2}$-in. steel bolts holding down the dome-shaped cover became so badly bent that they could no longer be used to make a reasonably tight joint the test was discontinued.

These experiments show conclusively:

First, that after the internal strains due to burning-in have been relieved by the cracking of the casting, no extension of these cracks will take place under the most severe abuse, and that there is no danger of a sudden failure of these castings; second, that a casting of this metal which does not contain burned-in patches will not crack spontaneously and in fact will not crack unless subjected to very high stresses; third, that defective castings may be welded fairly successfully by the oxy-acetylene method if preheated before welding and allowed to cool slowly after welding, provided that the original metal is fairly clean and that the casting has no machined surfaces, as these are liable to be badly distorted; that is, the method is best adapted to unfinished castings.

The welding experiments were made for the Board of Water Supply by Mr. S. W. Miller of the Rochester Welding Works, at Rochester, N. Y.

All the tests described were carried out under the direction of J. Waldo Smith, Chief Engineer of the Board of Water Supply of the City of New York.

Mr. Howe. MR. HENRY M. HOWE *(by letter)*.—The rise of cohesion on slight reheating, as indicated by the Brinell scleroscope and tensile tests concurrently, and its reversal when the annealing temperature rises slightly beyond 200° C., resemble what takes place in over-strained iron and steel. How may these phenomena be explained? In annealing we have three changes at work:

1. The recrystallization of the amorphous metal, weakening;
2. The release of stress, strengthening;
3. The microscopic coalescence of particles, weakening.

These three influences are at work continuously, but at different rates, and consequently with different net effects at different periods. The rise of the cohesion from zero to about 200° C. indicates that in this range the strengthening caused by the removal of stress outweighs the weakening caused by the two other agencies. This is in accordance with the remarks of Merica and Woodward.[1] **Mr. Howe.**

This rise of cohesion on slight reheating is even more strikingly true of over-strained steel. This has been known and it has been taken advantage of for a very long time. W. H. Payne found, between 1856 and 1861, that drawing cold-rolled steel through a bath of molten tin, zinc, or lead raised its transverse elastic limit, and this method is said to have been used for the wires of the Brooklyn Bridge, which were thereby increased both in tensile strength and in elastic limit.[2] This strengthening effect of gentle heating has been re-discovered independently by a great number of investigators.

---

[1] See pp 167-168 and 173-178.—ED.

[2] The writer, "The Metallurgy of Steel," p. 214, 1890.

THE EVALUATION OF ZINC DUST: A PROPOSED METHOD OF ANALYSIS.

By L. A. Wilson.

SUMMARY.

This paper deals with the evaluation of zinc dust from the viewpoint of its metallic zinc content. A brief résumé of previous work is given, together with a discussion of the several classes of analytical methods. The "hydrogen evolution method" is described in more detail, as the proposed method given later in the paper is based on this.

The object of the paper is to present a method of analysis and arrangement of apparatus that will render the analysis of zinc dust simple, accurate and rapid. The method of analysis is similar to that ordinarily used in the hydrogen evolution method. However, the importance of maintaining solutions saturated with hydrogen and minimizing temperature variations is emphasized. The arrangement of apparatus eliminates sources of error inherent with previously proposed apparatus and decreases the time required for analysis. A drawing is included which shows this arrangement.

Where laboratory temperature is kept constant, a "correction tube" may be used for correcting the volume of hydrogen to standard conditions, or directly into per cent of metallic zinc, thus eliminating long calculations. This correction tube is also illustrated.

The paper also includes a set of curves showing the change of vapor tension of water above water and dilute sulfuric acid with temperature. These curves are useful in correcting the volume of hydrogen to standard conditions, whether calculated from the elementary formula or the correction tube.

The results of many determinations have shown the proposed method to give more accurate results than any other tried.

THE EVALUATION OF ZINC DUST: A PROPOSED METHOD OF ANALYSIS.

By L. A. Wilson.

Introduction.

Zinc dust, or "blue powder" as it is commonly known, is being used in constantly increasing amounts for organic reductions, sherardizing, precipitation of gold and silver in cyanide practice, and in certain classes of paint.

Due to the demands of the trade for a material superior to the ordinary spelter furnace blue powder, the zinc dust sold to-day is largely a specially prepared product. The two particular qualities usually demanded by the consumers of zinc dust are fineness and high metallic zinc content.

The fineness is best determined by microscopical examination, but as usually carried out in practice, it is a simple matter of carefully screening a sample through a nest of screens. On the other hand, the determination of the metallic zinc content, or reducing power as metallic zinc, is not so easily obtained and determinations by different methods or even by the same method with different analysts will show considerable variations. Since the manufacturer analyzes his product to maintain the grade, and the consumer is likely to analyze the zinc dust which he buys to preclude against accepting inferior material, there is need for a standard method that may be followed without great detail, and which will obviate the misunderstandings originating from variant analyses. It is the purpose of this paper to cover only the determination of the metallic zinc content of zinc dust, and not its physical properties.

After experimenting with the various proposed methods, the hydrogen evolution method was adopted because it was found to give the most consistently accurate results. The method and apparatus to be described later are the outcome of experimental work extending over several years, starting with the apparatus proposed by Franz Meyer and adding improvements and modifications as the work progressed. The method and apparatus have been used for hundreds of determinations for metallic zinc in zinc dust, and have given more accurate results than any method described in the literature. For this reason they are proposed as a standard means for determining the metallic zinc content of zinc dust.

RÉSUMÉ OF METHODS PROPOSED.

A description of all the methods of analysis proposed for the evaluation of zinc dust will not be given here, as they may be found in the literature. Practically all are based upon the reducing power of the zinc dust. This may be determined in any one of many ways, although the results from different methods will not be concordant, due to the inaccuracies inherent with most of the methods.

Fresenius dissolved the zinc dust in dilute sulfuric acid, and after drying passed the hydrogen over heated copper oxide in a combustion tube, absorbing the water formed in a U-tube and weighing. This method is accurate but long and tedious.

Drewsen used a known quantity of standard potassium-chromate solution for reduction by the zinc dust. The excess of chromate solution was titrated with ferrous sulfate and from the amount of chromate reduced, the metallic zinc content was calculated.

De Koninck found that ferric ammonium sulfate accelerates the reduction of chromate. With this he used a potassium-dichromate solution rather than one of the normal chromate.

Wahl gave a rapid method for evaluating zinc dust, based upon the reduction of neutral ferric sulfate in solution. The resulting ferrous sulfate was titrated with potassium permanganate and the percentage of metallic zinc calculated.

Beilstein and Jawein carried out the evaluation by conducting the hydrogen, resulting from the reaction of the zinc dust and dilute sulfuric acid, into a flask filled with water and measuring the amount of the latter displaced.

Kosmann and Liebschutz carried out determinations by moistening the sample of zinc dust with alcohol, and adding a warm neutral solution of copper sulfate. The mixture was slightly acidified, the copper separated, washed, dissolved, and determined.

Morse made determinations of the metallic zinc content by measuring the hydrogen gas evolved with acid in a Eudiometer.

Topf used a weighed quantity of iodine to oxidize the metallic zinc in the zinc dust and then titrated back the excess of iodine.

Barnes also used the volume of hydrogen gas liberated, devising a special apparatus for its measurement.

Weil made determinations by treating the zinc dust sample with cupric-chloride solution and titrating the excess copper with stannous-chloride solution.

Klemp has worked out a method of determining the metallic zinc content of zinc dusts by reduction of potassium iodate in alkaline solution.

Fraenkel modified Drewsen's method by adding potassium iodide to the solution containing the excess of bichromate remaining after the reaction with the zinc dust, and titrating the liberated iodine with standard sodium thiosulfate.

Besides the apparatus of Morse and Barnes for the volumetric determination of zinc dust, there have been many others. The best of these is that proposed by Franz Meyer. This apparatus has been widely used and with proper precautions excellent results may be obtained.

De Koninck and Grandy made comparative investigations of the several methods proposed up to 1902 and concluded that the gasometric determination of the hydrogen evolved gave the most precise results.

More recently Sharwood and Herz have proposed using the precipitation of silver from a solution of silver cyanide in potassium cyanide as a means of evaluating zinc dusts.

CLASSIFICATION AND DISCUSSION OF PROPOSED METHODS.

From the brief outlines of the methods given, it will be seen that they may be grouped into three classes, and that a discussion of inherent errors and accuracy for any one method is also generally applicable to the class in which that method belongs.

(*a*) *The Reduction of a Known Amount of Oxidizing Agent.*— The bichromate method is simple and rapid. The reduction theroretically proceeds without evolution of hydrogen gas but this is probably not always true. It frequently happens that particles of zinc dust will be seen floating on top of the solution with bubbles of hydrogen attached. The reaction with the acid in the solution is an inherent error in this method. The tendency is hence to get low results since the reaction of the zinc dust with acid results in less bichromate being reduced.

The volumes of standard solutions used in carrying out the bichromate method are relatively small, compared with the volume of hydrogen gas which the same weight of zinc dust would liberate. The accuracy required in standardizing, reading of burettes, and determining the end point on titration, is of a much higher order than that required in the hydrogen evolution method.

The ferric sulfate method is based on the reduction of the oxidizing agent, ferric sulfate, in neutral solution. The ferric sulfate requires careful preparation for this work. The reduction theoretically proceeds without evolution of hydrogen gas. The results obtained by this method are lower than those obtained by the hydrogen evolution method. The only explanation for this difference is the possible hydrolysis of the ferric sulfate and the reaction of the zinc dust with the small amount of sulfuric acid formed. In this case the hydrogen liberated would not be visible, but remain dissolved.

(b) The Precipitation from Solution of a Metal with Lower Solution Pressure than Zinc, i. e., Lower in the Electropotential Series than Zinc.—The precipitation of a metal from a solution, for example copper or silver, by zinc dust does not give the metallic zinc content of the precipitant, but merely an empirical result influenced by many factors. The three most important of these are the fineness of the zinc dust, the kind and condition of the solution, and the equilibrium that is reached between the metal and the zinc with their respective ion concentrations in solution. It is obvious that when a particle of zinc dust becomes completely coated with the precipitated metal, it cannot throw out more of the latter. For this reason the method using the precipitation of silver from a solution of silver cyanide in potassium cyanide is not to be considered as a method for actually determining the metallic zinc content of zinc dust, although it may give an indication of its so-called "Precipitation Efficiency," as applied in cyanide practice.

(*c*) *The Solution of the Zinc Dust with Acid and the Measurement of the Volume of Hydrogen Liberated.*—The hydrogen evolution method is the one most used by reputable analysts and laboratories. It is based on measuring the volume of hydrogen gas evolved from the action of zinc dust on pure dilute sulfuric acid. This volume is then calculated to standard conditions (correcting for the vapor tension of water). The percentage of metallic zinc is determined, from the relationship that, at standard conditions, one gram of pure zinc liberates 342.5 cc. of hydrogen.

The Franz Meyer apparatus, with subsequent improvements, is described in Scott's "Standard Methods of Chemical Analysis." This apparatus has the disadvantage of generating the hydrogen gas adjacent to the outlet for the liquid being displaced. Consequently, small bubbles of hydrogen and often small particles of zinc dust are carried out with the displaced liquid. All gas in the rubber tubing connecting the apparatus with its leveling bottle must hence be returned before the volume of gas is measured. It frequently happens that the zinc dust particles may be transported as far as the leveling bottle, in which case the results obtained will be worthless. However, both of these causes for error may be eliminated by inserting a relatively large glass tube between the apparatus and the leveling bottle. The flow of displaced liquid through this tube will then be much slower than through the rubber tube and opportunity is afforded for the complete solution of the fine particles of zinc dust, and the coalescing of the small bubbles. When the solution of the zinc dust sample has gone to completion, the gas in this side tube is transferred to the measuring tube, the total volume read and the metallic zinc content calculated.

The Meyer apparatus has also the other disadvantage of being slow in operation. The descent of acid into the decomposing flask is through a small bore in the stopcock and into the water where it becomes greatly diluted before reaching the zinc dust. When sufficient acid has reached the zinc dust the gas generated rises and passes through this same bore, thus slowing down the subsequent rate of acid entering.

The use of a factor to correct for the solubility of hydrogen in water and acid is not entirely satisfactory, even though determined with c. p. zinc. The solubility of hydrogen is affected by temperature and the factor must include a temperature correction. Furthermore the volume of liquid in contact with hydrogen long enough to become saturated, is not the same in any two tests, although the volume of liquid in the system may be the same in each case. The liquid first displaced will have practically no hydrogen dissolved and the last will be saturated, so that the rate of gas evolution will materially affect the amount dissolved and carried out by the displaced liquid, and therefore, affects the factor to be employed. When correcting by a factor the repeated use of the 10-per-cent sulfuric acid for several determinations, as is commonly practised, will give inaccurate results. Errors from this source can be avoided by starting with all solutions saturated with hydrogen and maintaining nearly constant temperature. No correction factor is then required.

Experience with these three types of methods on all grades of zinc dust and granulated c. p. zinc has proven that the hydrogen evolution method will give more accurate results than any other method recommended. This more than compensates for the longer time required for making the determination.

PROPOSED STANDARD METHOD.

The procedure and apparatus recommended for this method are fundamentally the same as in the Franz Meyer method. By re-arrangement of apparatus and improvements in details of the procedure, the accuracy of determining the metallic zinc content of zinc dusts has been raised and the time required materially shortened. The average time required for high-grade zinc dust of which 90 to 95 per cent passes a 350-mesh sieve, and contains less than 0.3 per cent of metallic impurities, is about 1½ hours, as against 2 to 4 hours with the Franz Meyer apparatus. With the latter apparatus there is no satisfactory way to speed up the determination, shaking being only mildly effective. In the proposed new method, the addition of strong acid accomplishes this purpose.

The method and apparatus may be best described with the aid of Fig. 1. A 1-g. sample of zinc dust is weighed and transferred as rapidly as possible to a small Erlenmeyer flask *A*, of

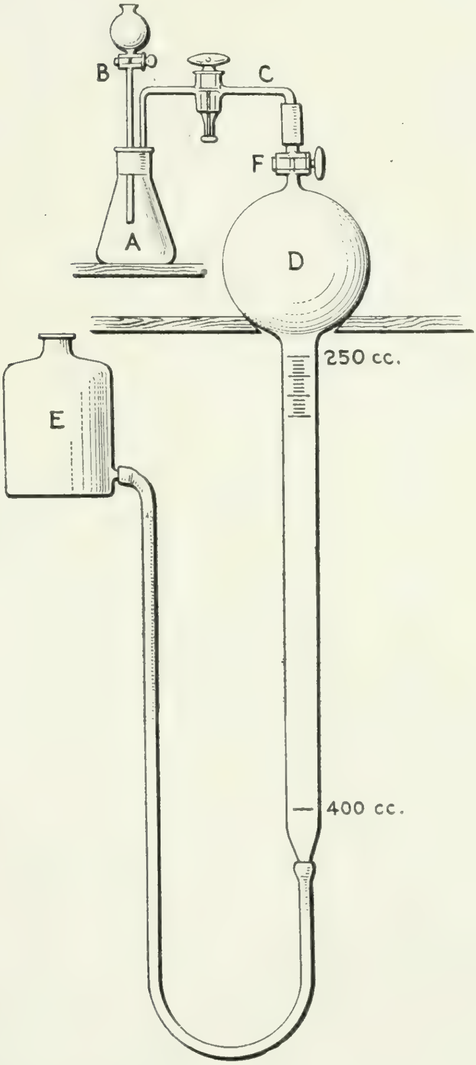


FIG. 1.—Apparatus for Evaluation of Zinc Dust.

100 or 200-cc. capacity, in which is placed a piece of sheet platinum about 1.5 cm. square. About 5 g. of clean unoxidized ferrous sulfate crystals are added on top of the zinc dust and the flask nearly filled with distilled water saturated at room temperature with hydrogen gas.

The object of adding the sheet platinum and ferrous sulfate is to increase the rate of hydrogen evolution by catalytic action. A further reason for adding the ferrous sulfate on top of the zinc dust sample is to coagulate the latter as much as possible when it becomes wetted, and thus prevent the floating of more than an unappreciable amount of the sample.

The rubber stopper containing separatory funnel *B* and connecting tube *C* is tightly inserted into the neck of the flask. A little distilled water is poured into *B* and the three-way stopcock in *C* turned to connect the flask with the downward outlet. Enough water is now run in from the separatory funnel to displace all the air in the flask and the connecting tube through the bore in its stopcock. The stopcock in *C* is now turned so that the downward outlet is in connection with the measuring tube *D*. By raising the leveling bottle *E*, containing 10-per-cent sulfuric acid also saturated with hydrogen at room temperature, all the gas in *D* is displaced. The stopcock in *C* is now turned through 90 deg., so as to connect the decomposing flask *A* with the measuring tube *D*. The system is hence completely filled with liquid and ready for the generation of hydrogen. The measuring tube *D* has a total capacity of 400 cc. and is graduated from 250 to 400 cc. by 0.25 cc.

Thirty cubic centimeters of 1:1 sulfuric acid are now poured into the separatory funnel. A small portion of this acid is allowed to run into the decomposing flask until a brisk but not too rapid evolution of hydrogen takes place. The acid, being much heavier than water, settles to the bottom of the flask and the action commences immediately. The gas evolved, together with some solution and a very small amount of zinc dust passes over into the measuring tube, displacing the acid there. When the action in the decomposing flask has slowed down, more strong acid is introduced until all has been added. During this time the acid in the measuring tube and flask is shaken so as to wash down the particles of zinc dust from the upper parts of the flask and tube now filled with gas. The particles in the measuring tube on coming in contact with the 10-per-cent sulfuric acid are readily dissolved and generate their portion of hydrogen.

When all the zinc dust has been dissolved, water is run in from the separatory funnel to force the hydrogen over into the measuring tube and to fill the flask and connecting tube with water through to the stopcock F, which is then closed. After leveling with the leveling bottle the volume of hydrogen generated from the 1-g. sample at the prevailing atmospheric conditions is read from the measuring tube. The percentage of metallic zinc in the sample is then calculated from the following expression:

$$\text{Per cent of Metallic Zinc} = \frac{V \times (P-p) \times 0.29196}{(1+0.00367\,t)\,760},$$

in which V = volume of gas in measuring tube at atmospheric conditions, P = barometric pressure, p = vapor tension of water above 10-per-cent sulfuric acid at room temperature, and t = room temperature.

Necessary Precautions.—To obtain results of the highest accuracy, it is necessary when weighing out samples of zinc dust which are very finely divided, to keep the time of exposure as small as possible in order to minimize the oxidation that takes place with the oxygen of the air. It is also highly important when samples are to be held, that they be kept in ground glass stoppered bottles, completely filled, and sealed with paraffin or wax.

The two variables most likely to affect the results are temperature and barometric pressure. A change in the barometric pressure is practically always extended over a reasonable length of time. A careful reading of the barometer when the volume of gas in the measuring tube is read will eliminate any error from this source. A temperature change, on the other hand, affects not only the volume of gas, according to Charle's law, but also affects the vapor tension of water and hence the actual pressure on the hydrogen when measured. Unlike barometric variations, changes in temperature can to a large extent be avoided by making the analyses in a room maintained at a nearly constant temperature, enclosing the apparatus in a cabinet, with door fronts that are opened only when measurements are to be taken, and keeping all water and acid saturated with hydrogen in this same cabinet.

The rubber connection between the connecting and measuring tubes must be of heavy rubber and should be shellacked.

APPARATUS FOR CORRECTING TO STANDARD CONDITIONS DIRECTLY.

Where a large number of metallic zinc determinations are carried out daily, the matter of calculating the results becomes laborious and is occasionally a point of error. This can be done away with in a simple manner.

A measuring tube, similar to the one used for measuring the gas, is sealed at the top below its stopcock, filled with mercury and placed in a glass cylinder containing mercury.

Hydrogen, perfectly dry, is now introduced until it fills less than half the graduated stem of the tube. After leveling, this volume is read very accurately together with the room temperature and pressure. As a check, this volume may be read at another temperature. The volume is calculated to standard conditions. Enough pure water is now introduced into the measuring tube to entirely cover the mercury. After equilibrium has been attained, the volume, temperature, and pressure are read and the dry volume of hydrogen calculated will check with the original volume introduced. Fig. 2 shows this apparatus in readiness for use.

The volume of gas in this tube will vary according to atmospheric conditions, but since the volume of dry gas at standard conditions is known, the factor to correct the volume of hydrogen gas evolved in a determination to standard conditions is a simple matter of calculation, as given by the following expression:

$$\text{Per cent of Metallic Zinc} = \frac{V_D \times v_s \times 0.29196}{v_d},$$

in which V_D = volume of gas evolved in determination, v_s = volume of dry hydrogen in correction tube reduced to standard conditions, and v_d = volume of hydrogen in the correction tube read at same time as V_D.

Where the amount of work carried out would warrant it, a table may be made up giving the factor for each graduation on the tube. The factor is the calculated result of $\frac{v_s}{v_d} \times 0.29196$, where v_d is the volume for each graduation. We can now directly convert the gas volume in the measuring tube after each determination directly over into percentage of metallic zinc.

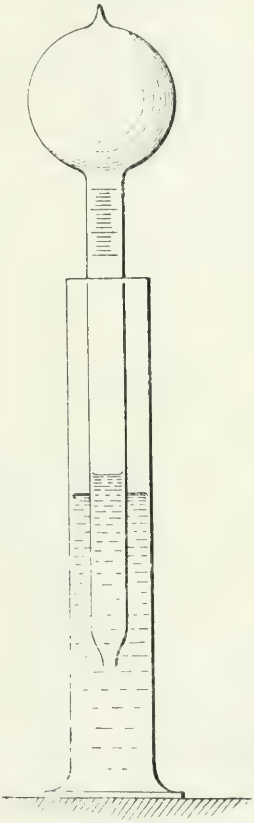


FIG. 2.—Correction Tube.

The vapor tension of water is slightly lower above 10-percent sulfuric acid than above pure water, and the error that would be introduced by taking the volumes in the correction

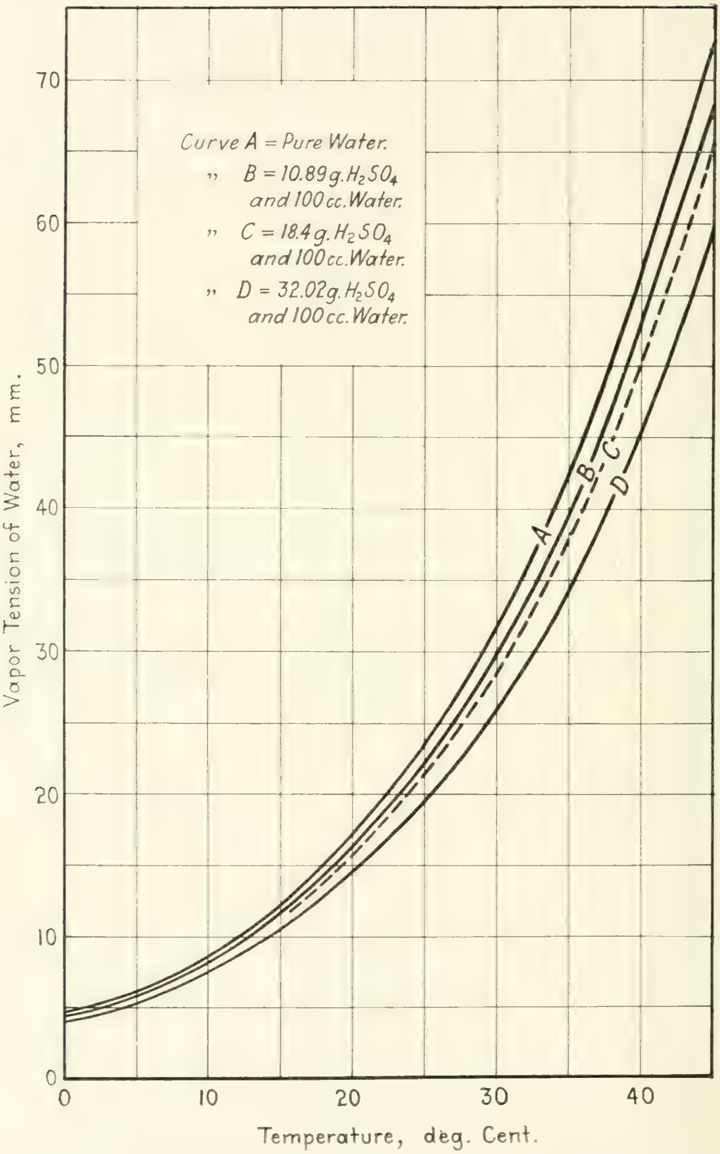


FIG. 3.—Vapor Tension of Water above Pure Water and Dilute Sulfuric Acid. Data for curves *A*, *B* and *D* from Landoll-Bernstein, page 167. Curve *C* interpolated.

tube directly would give results ordinarily about 0.3 per cent low.

The table of factors calculated is corrected to take this into account. This difference is indicated in Fig. 3, which shows the curves of vapor tension of water above pure water and dilute sulfuric acid plotted against temperature. The curves are for the following:

A = Vapor tension above pure water;

B = Vapor tension above sulfuric acid containing 10.89 g. H_2SO_4 and 100 cc. water;

C = Vapor tension above sulfuric acid containing 18.4 g. H_2SO_4 and 100 cc. water. This solution is 10-per-cent HSO_{24} by volume and the curve was obtained by interpolation, using curves *B* and *D*;

D = Vapor tension above sulfuric acid containing 32.02 g. H_2SO_4 and 100 cc. water.

It will be seen from curves *A* and *C* that where the temperature changes over a large range the use of a correction tube will give slightly erroneous results, due to the increasing difference in vapor tension above water and 10-per-cent sulfuric acid with increasing temperature. In this case, results should be calculated using the elementary formula. Where the laboratory temperature is controlled, the correction tube gives satisfactory results and is a valuable additional piece of apparatus.

In this proposed method all known possibilities of error have been taken into account and accurate reproducible results are obtained. The results of many analyses extending over a long period of time, and the running of many check samples as unknowns, have confirmed this and prompt the putting forward of this method and apparatus as a standard means for determining the metallic zinc content of zinc dust.

BIBLIOGRAPHY.

Fresenius	*Zeitschrift für Analische Chemie*, Vol. 17, 1878.
Drewsen	*Zeitschrift für Analische Chemie*, Vol. 19, 1880.
De Koninck	*Bulletin*, Assoc. Belge des Chem., Vol. 11, 1897.
Minor	*Chemische Zeitung*, Vol. 14, 1890.
Wahl	*Journal*, Soc. Chem. Ind., Vol. 16, 1897.
Beilstein and Jawein	Ber. der Chem. Ges., Vol. 13, 1880.
Kosmann	*Chemische Zeitung*, Vol. 9, 1885.
Liebschutz	*Zeitschrift für Analische Chemie*, Vol. 25, 1886.
Morse	*American Chemical Journal*, Vol. 7, 1885.
Topf	*Zeitschrift für Analische Chemie*, Vol. 26, 1887.
Barnes	*Chemical News*, Vol. 43, 1881.
Klemp	*Zeitschrift für Analische Chemie*, Vol. 29, 1890.
Meyer	*Zeitschrift für Angewande Chemie*, Vol. 7, 1894.
Bach	*Zeitschrift für Angewande Chemie*, Vol. 7, 1894.
Bodländer	*Zeitschrift für Angewande Chemie*, Vol. 8, 1895.
De Koninck and Grandry	*Bulletin*, Assoc. Belge des Chem., Vol. 16, 1902.
De Koninck	*Bulletin*, Assoc. Belge des Chem., Vol. 17, 1903.
Sulton	"Volumetric Analysis," Eighth Edition, p. 385.
Nissenson	"Untersuchungs Methoden."
Liebig	"Zinc und Cadmium," p. 30.
W. J. Sharwood	*Engineering and Mining Journal*, Vol. 93, 1912; also p. 165.
N. Herz	*Bulletin 104*, Am. Inst. Min. Eng., 1915.
W. J. Sharwood	*Bulletin 129*, Am. Inst. Min. Eng., 1917.
J. E. Clennell	*Engineering and Mining Journal*, Vol. 95, 1913.
Scott	"Standard Methods of Chemical Analysis," Second Edition Revised, p. 487.

PROPORTIONING THE MATERIALS OF MORTARS AND CONCRETES BY SURFACE AREAS OF AGGREGATES.

By L. N. Edwards.

SUMMARY.

The fundamental principle underlying the formation of mortars is that the constituents should be so proportioned as to give desired physical properties. Since cement is the only strength-producing constituent entering into the mix, its proportioning will have the greater effect and should receive the greater attention. The "surface-area" method of proportioning assumes as its basic principle that the physical properties are primarily dependent upon the relation of the volume of cementing material to the surface areas of the aggregates.

This paper has for its object the following:

1. To develop information relating to the average surface areas of sand and stone aggregates.

2. To describe the methods and materials used, the results obtained, and the phenomena observed in a series of experimental tests undertaken to develop the practical application and efficacy of this method.

The results obtained show:

1. That with materials of uniform quality this method provides a means of securing uniformly strong mortars and concretes from sand aggregates of varying granulometric composition.

2. That the strengths of mortars are dependent upon (1) the quantity of cement in relation to the surface areas of the aggregates, and (2) the consistency of the mix.

3. That the strengths of mortars of uniform consistency containing sand aggregates of varying granulometric composition are directly proportional to the quantity of cement they contain in relation to the surface area of the aggregate.

PROPORTIONING THE MATERIALS OF MORTARS AND CONCRETES BY SURFACE AREAS OF AGGREGATES.

By L. N. Edwards.

The use of mortars dates from a time so remote that its beginning cannot be ascertained.[1] However, its modern use in the form of an intimate mixture of lime or cement, sand and water doubtless dates back to the "constructive" Roman period. "Both Romans and Normans well understood its use, both had a thorough knowledge of mortar."[2]

Doubtless the method of proportioning the cementing material and aggregates by volume originated among these early artisans. However, the earliest authentic record of its use is credited to General Pasley (1827). This method as commonly specified and used is not only illogical and unscientific, but also unfair to the development of the true value of the materials entering into the composition of both mortar and concrete.

Cement is the binder holding together the aggregates. The fundamental theory of the combination is that the two materials, the one active, the other inert, act as a single unit.

With regard to the item of strength, the ideal mortar contains a proportion of cement sufficient to develop the full strength of the particles of sand aggregate; while the ideal concrete contains a mortar component, in itself ideal, which will develop the full strength of the particles of stone aggregate. The actual proportioning and combining of the cement and aggregates fall somewhat short of reaching this theoretical perfection; practical considerations render it impossible to distribute the cement perfectly, and thus to secure that absolute adhesion between the particles of aggregate which is necessary to the perfect transmission of the stresses from one particle of aggregate to another. Perfection in this regard is, therefore, unattainable at least in so far as commonly used field methods and operations are concerned.

---

[1] "South American Archeology," T. A. Joyce, 1912; "The Pyramids and Temples of Gizeh (Egypt)," W. M. Flinders Petrie, 1883.

[2] "Concrete, Its Use in Building," Thomas Potter, 1908.

Those having experience in practical tests of mortar and concrete know that with given volumetric proportions of materials comparatively slight variations in the granulometric composition of the sand aggregate produce marked differences in the strength, toughness, and other physical properties of the product.

There should be no place in engineering for guesswork and empiricism whenever scientific determination is possible. With this idea in mind and with a due allowance for the practical considerations mentioned above, it remained to set about the task of finding a structural reason for the wide variations of strength obtained in mortar tests. In November, 1917, a most natural solution presented itself, namely:

1. The strength of mortar is primarily dependent upon the character of the bond existing between the individual particles of the sand aggregate. Upon the total surface area of these particles depends the quantity of cementing material. Furthermore:

2. The amount of water required to produce a "normal," uniform consistency of mortar is a function of the cement and of the surface area of the particles of the sand aggregate to be wetted.

This idea of proportioning the cement in relation to the surface area of the aggregate was new to the author and appealed to him as a reasonable, although rather radical, departure from the time-honored practice of proportioning by volume measurement. However, he discovered in February, 1918, that it is in reality at least twenty-five years old. Prof. A. H. Heath describes t very clearly in his book[1] as here quoted:

> "Sufficient cement should be used to furnish a coating to the surface of each particle of the matrix, and the extent of surface of particles as compared with their bulk is much greater with fine sand than with coarse sand. For instance, a 3-in. sphere has one-eighth the bulk of a 6-in. sphere, but its surface area is one-fourth that of the 6-in.
>
> "To ensure the perfect coating of each particle, a larger proportion of cement must be taken with fine than with coarse sand. If the proportion of

---

[1] "A Manual of Lime and Cement," 1893.

cement taken for fine sand be that sufficient only for coarse sand, the cement films enveloping the particles will probably be imperfect, and the concrete will be deficient in strength."

No attempt was made by Professor Heath to develop the surface-area method of proportioning, of which he was a pioneer or possibly the originator.

This paper presents the results of tests made by the City of Toronto, Department of Works, under the direct supervision of the author.

OBJECT AND SCOPE OF TESTS.

The tests were made with the object of developing the surface-area method of proportioning and securing information relative to (1) the surface area of aggregates of varying granulometric composition; (2) the quantity of water necessary to produce a "normal," uniform consistency of mortar for varying sands and cement content; and (3) the strength of mortar attained by varying the proportion of cement in the mix.

The range or scope of the tests was sub-divided as follows:

1. The determination of the average surface area of sand and stone particles of varying sizes based upon an actual count of the number of particles in given weights.
2. The determination, by trial, of the quantity of water necessary to produce, for any given sand and proportion of cement, a mortar of "normal," uniform consistency.
3. The determination of the reliability of the surface-area method of proportioning mortars in so far as strength alone is concerned.
4. The determination of the relative strengths resulting from variations in the cement content of mortars within practical limits.
5. The securing of miscellaneous general information pertaining to the foregoing phases of the tests.

The investigations herein described involve compression and tension tests upon 240 mortar cylinders, 2 in. in diameter by 4 in. long; 45 concrete cylinders 6 in. in diameter by 12 in. long; and 324 standard briquettes.

SURFACE AREA OF AGGREGATES.

Possibly the fact that the relation of the surface areas to the volumes of particles of matter depends upon their size and shape needs no demonstration; however, the following example will serve to bring this fact more clearly to mind:

Assume three masses of material, each made up of the following particles:

1. Spheres 2 in. and $\frac{7}{8}$ in. in diameter.
2. Spheres 2 in., $1\frac{7}{16}$ in. and $\frac{9}{16}$ in. in diameter.
3. Spheres $1\frac{3}{4}$ in. and 1 in. in diameter, 1-in. cubes, and parallelepipeds $\frac{1}{4}$ by $\frac{1}{2}$ by $\frac{1}{2}$ in. and $\frac{1}{2}$ by 1 by 1 in.

Assume now one cubic foot of each and that the particles are regularly arranged as shown in Fig. 1. Both the total surface area and the total volume in each cubic foot are readily determined. They are as shown in Table I.

TABLE I.—RELATION OF SURFACE AREA TO VOLUME OF PARTICLES.

Cubic Foot No.	Surface Area, sq. in.	Volume, cu. in.	Relation of Area to Volume.	Relation to No. 1.	
				Area, per cent.	Volume, per cent.
1..........	4474.3	1372.4	3.26 : 1	....	....
2..........	4545.9	1281.0	3.55 : 1	1.6 greater	6.6 less
3..........	5444.0	1065.8	5.11 : 1	21.9 "	22.3 "

The shapes of particles of sand and of stone aggregates are infinite in number and for this reason no accurate determination of their surface areas is possible. However, it is reasonable to assume that these areas can be closely approximated. Doubtless these approximate areas do not vary greatly from the true areas in the finer particles of sands, since these particles, when examined under the microscope, appear more nearly spherical than do the larger particles of sands and of gravels.

Surface Area of Sand Aggregate.—As a preparation for the securing of information from which it would be possible to compute the approximate average surface area of sand particles of varying sizes (the exact area cannot be determined) samples of natural sands were secured from different localities. Each sand was thoroughly dried and divided by sieving into its component sizes.

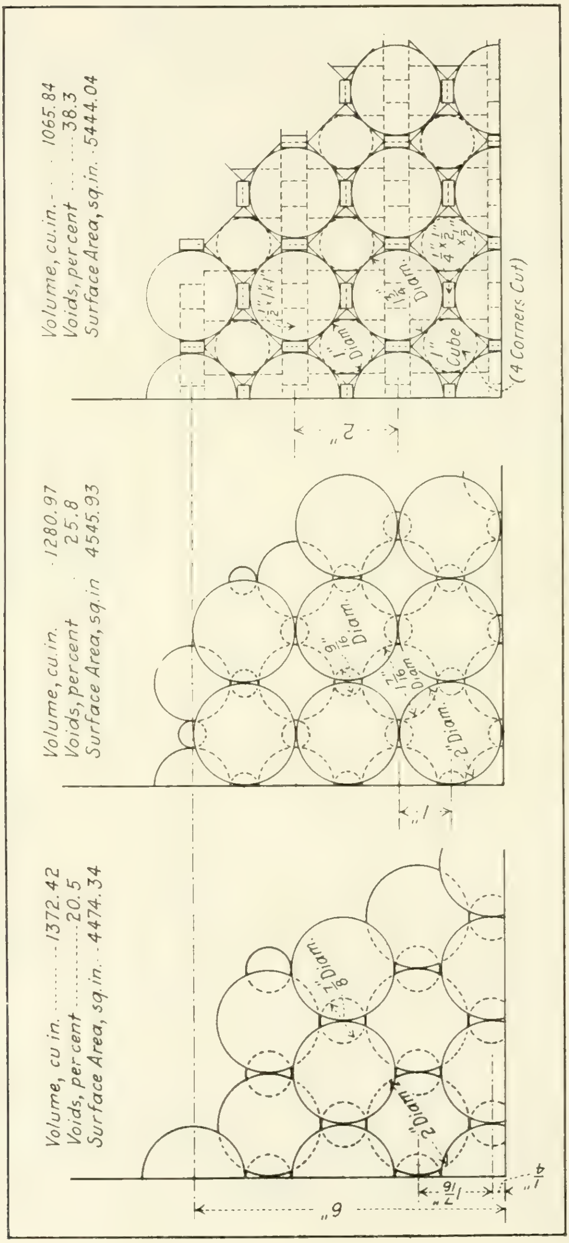


FIG. 1.—Relation of Surface Area to Shape of Particles.

For each sand the average number of particles per gram was determined, for every size of each sand, by an actual count. For the larger sizes 8 to 10 g. or more, and for the medium sizes 3 to 5 g. were counted; while for the smaller sizes 0.25 to 1 g. was counted. The results of these counts, together with the actual and the assumed averages for computation purposes, are given in Table II.

The number of particles per gram having been determined as above described, the specific gravity being 2.689 and the weight of water being assumed at 62.37 lb. per cu. ft., the volume per particle was computed as follows:

TABLE II.—NUMBER OF SAND PARTICLES PER GRAM.

Name of Sand.	Size of Sieve Passed and Retained on.							
	P4–R8	P8–R10	P10–R20	P20–R30	P30–R40	P40–R50	P50–R80	P80–R100
"Maple" Vaughan, Ont.	14.75	56.28	40.356	1729	5686	16 891	45 086	72 511
"Pleasant Lake" Otisfield, Me.	12.60	58.80	40.200	1673	5020	12 183	39 876	98 996
"Cataract" Caledon, Ont.	10.93	56.17	366.70	1431	4308	15 010	39 510	102 116
"Erin" Erin, Ont.	13.25	49.80	270.12	1449	4439	17 999	34 542	125 630
"Ontario Lake" Toronto, Ont.	17.16	57.83	214.00	1409	4584	17 675	40 422	96 412
"Standard Ottawa" Ottawa, Ill.	....	....	....	1323	....	....	....	....
Average	13.74	55.78	331.28	1502	4806	15 991	40 057	99 133
Assumed Average for Tests	14	55	350	1500	4800	16 000	40 000	99 000

$$\text{Weight of sand material} = 62.37 \times 2.689 = 167.713 \text{ lb. per cu. ft.}$$
$$= 0.09706 \text{ lb. per cu. in.} = 43.0257 \text{ g. per cu. in.}$$

Then

$$43.0257 \times \text{number of particles per gram} = \text{number of particles having a total volume of 1 cu. in.}$$

Whence,

$$\text{Average volume per particle} = \frac{1}{\text{Number of particles having volume of 1 cu. in.}}$$

The average volume per particle being determined, the shape of the particles was assumed as spherical and the surface area per particle and per gram of sand was determined accordingly. The results of these computations are given in Table III. These results, in part, are also shown graphically in Fig. 2. This curve of areas, although empirical, approximates very closely the curve represented by the equation $xy = 139$.

Surface Area of Stone Aggregate.—The shapes of particles of broken stone and of natural gravels are dependent mainly upon the character of the rock material of which they are composed, whether of igneous or of sedimentary origin. The former produce, in broken stone, particles more angular in shape and more rough of surface than the latter; while in gravels the tendency of the former is to produce particles approximating more nearly spheres; the particles of the latter are commonly flattened with rounded edges.

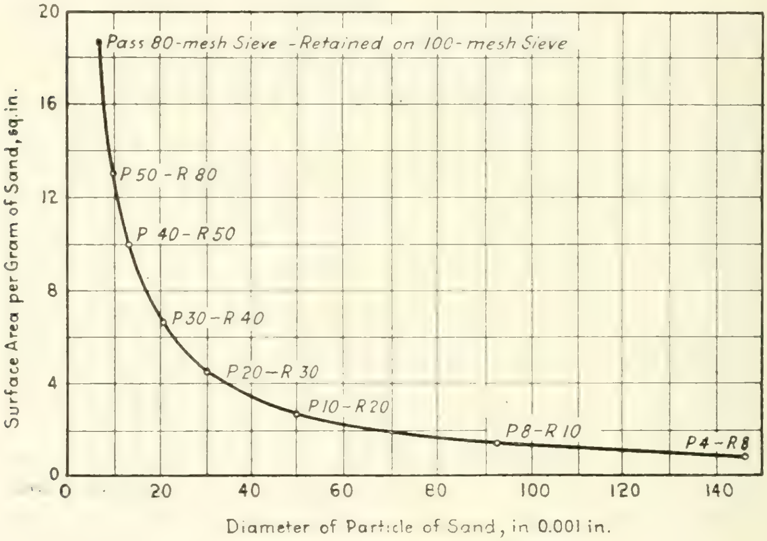


FIG. 2.—Surface Area of Sand Aggregate.

The method above described for sand aggregates was followed in the counting of particles, computation of average volumes, etc. In the determination of average surface areas the particles of broken stone were assumed to be made up of one-third cubical and two-thirds parallelepipedal shapes, the latter sub-divided to approximate more closely the areas of the

TABLE III.—VOLUME AND SURFACE AREA OF SAND.

Sieve Passed and Retained on.	Number of Particles per Gram.	Average Volume per Particle, cu. in.	Average Diameter per Particle, in.	Surface Area per Particle, sq. in.	Surface Area per Gram, sq. in.
P 4 - R 8............	14	0.001 66	0.146 95	0.0678	0.9492
P 8 - R 10	55	0.000 4226	0.093 1058	0.027 2335	1.4978
P 10 - R 20...........	350	0.000 066 45	0.050 2534	0.007 9338	2.7778
P 20 - R 30...........	1 500	0.000 015 49	0.030 928	0.003 0055	4.5083
P 30 - R 40	4 800	0.000 004 842	0.020 9893	0.001 3841	6.6437
P 40 - R 50...........	16 000	0.000 001 452	0.014 0818	0.000 6201	9.9216
P 50 - R 80...........	40 000	0.000 000 5815	0.010 3568	0.000 336 913	13.4765
P 80 - R 100..........	99 000	0.000 000 2348	0.007 6538	0.000 188 325	18.6442
Standard Ottawa.......	1 323	0.000 017 57	0.032 2545	0.003 268 38	4.3241

TABLE IV.—VOLUME AND SURFACE AREA OF STONE AGGREGATE.

BROKEN STONE.

Screen Passed and Retained on.	Number of Particles in 100 lb.	Average Volume per Particle, cu. in.	Surface Area per Particle, sq. in.	Surface Area per 100 lb., sq. ft.
P 2 - R $1\frac{1}{2}$........	670	1.553	8.7047	40.5
P $1\frac{1}{2}$ - R 1	1 680	0.636	4.9261	57.47
P 1 - R $\frac{3}{4}$..............	5 680	0.1811	2.1139	83.38
P $\frac{3}{4}$ - R $\frac{1}{2}$................	14 900	0.0692	1.1943	123.58
P $\frac{1}{2}$ - R $\frac{1}{4}$..............	43 820	0.0236	0.5339	162.47

SCREENED GRAVEL.

Screen Passed and Retained on.	Number of Particles in 100 lb.	Average Volume per Particle, cu. in.	Average Diameter per Particle, in.	Surface Area per Particle, sq. in.	Surface Area per 100 lb., sq. ft.
P 2 - R $1\frac{1}{2}$	430	2.4289	1.6678	8.7383	26.09
P $1\frac{1}{2}$ - R 1	1 090	0.9509	1.2201	4.6764	35.39
P 1 - R $\frac{3}{4}$.....	3 830	0.2694	0.8013	2.0330	54.00
P $\frac{3}{4}$ - R $\frac{1}{2}$......	10 030	0.1020	0.5797	1.0557	73.54
P $\frac{1}{2}$ - R $\frac{1}{4}$......	37 330	0.0276	0.3753	0.4425	114.71

elongated and slab-like shapes of particles. Gravel particles were assumed as spherical in shape. The results obtained for various sizes of particles are shown in Table IV. Fig. 3 shows graphically a portion of these results.

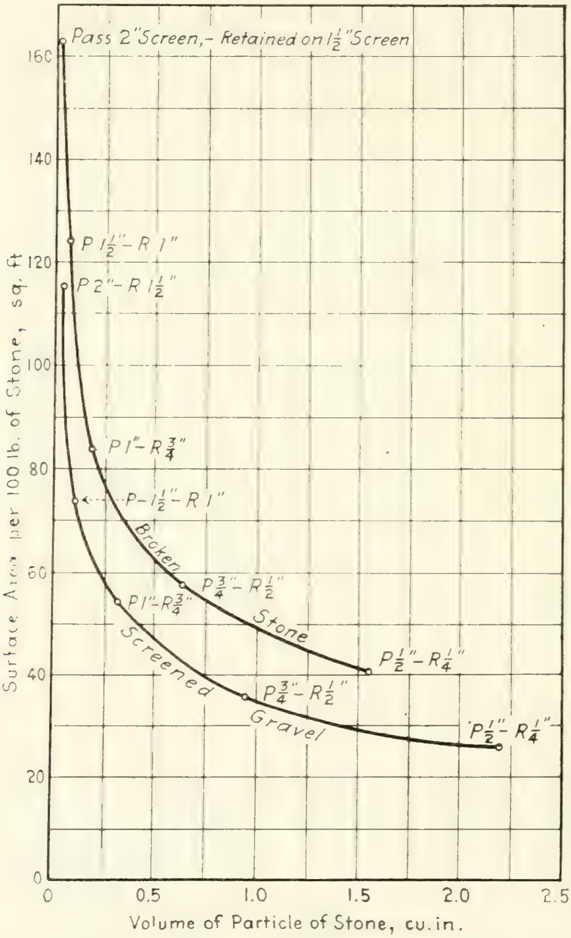


FIG. 3.—Surface Area of Stone Aggregate.

MATERIALS USED IN TESTS.

The properties of the cement, of the sand and stone aggregates, and of the water used in the preparation of test specimens were as follows:

Cement.—The Portland cement was, with the exception of that used in the "Consistency Tests," a combination of two brands, namely, "Canada" and "Pyramid." The former was manufactured by the Canada Cement Co., Limited, Montreal, Que., and the latter by the St. Marys Portland Cement Co., Limited, St. Marys, Ont. The two brands were thoroughly mixed by first pouring them together from separate receptacles, then by sieving them several times through a No. 20 sieve.

Following are the physical properties determined in accordance with the Standard Specifications and Tests for Portland Cement (C 9–17) of this Society[1]:

PHYSICAL PROPERTIES.

Constancy of volume		O. K.
Specific gravity		3.12
Initial set, minutes		195
Final set, minutes		450
Fineness.		
Per cent retained on	No. 100 sieve	3.8
	No. 200 sieve	21.8
Tensile strength, lb. per sq. in.		
Neat	24 hours	312
	7 days	677
	28 days	707
Mortar	7 days	265
	28 days	388

Sand.—All sand used in the tests was of limestone origin, and with the exception of that in one concrete test was secured from the Lake Shore Sand and Gravel Co., Limited, Toronto, Ont. This sand was dredged from a deposit in Lake Ontario, and was free from clay or other deleterious matter. Its chemical composition was as follows:

Loss on ignition, per cent	16.51
Silica, per cent	42.81
Iron and aluminum oxides, per cent	11.76
Calcium oxide, per cent	24.47
Magnesia, per cent	1.68

The specific gravity of this sand taken at 70° F. was 2.689.

---

[1] 1918 Book A.S.T.M. Standards, pp. 503-504.—ED.

The original sand was thoroughly dried upon a metal heater and, to remove the larger material, was passed through a sieve having 4 meshes per linear inch. All material passing this sieve was then divided into the portions retained upon a standard set of 8-in. diameter hand sieves having 8, 10, 20, 30, 40, 50, 80, and 100 openings per linear inch. The portions secured were placed in bags and carefully labeled for identification.

The sands used in concrete tests were not sub-divided as above described, and, in consequence, they contained small percentages of "dust" passing a No. 100 sieve.

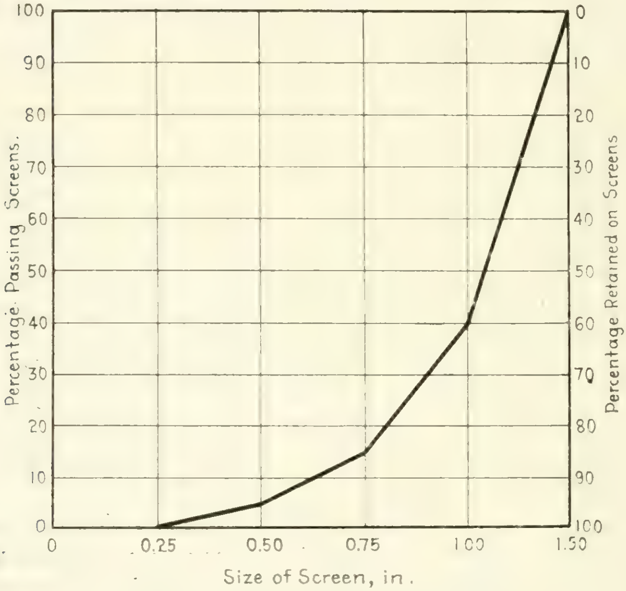


FIG. 4.—Grading of Broken Stone.

Stone.—The crushed stone used in the concrete tests was a composite lot secured from several quarries in Ontario. It was, in general, a dark colored limestone of good quality. Prior to use, this material was divided into the portions retained upon 1, $\frac{3}{4}$, $\frac{1}{2}$ and $\frac{1}{4}$-in. screens. No material was larger than that retained upon a 1-in. screen. The grading of the stone as used is shown graphically in Fig. 4. Its weight was 87 lb. per cu. ft.

Water.—All water used in the tests was taken from the city water mains, the source of supply being Lake Ontario. The chemical analysis is as follows:

	PARTS PER MILLION.
Total solids	120.0
Alkalinity (lacmoid) bicarbonates 103; carbonates 2	105.0
Permanent hardness	32.5
Total hardness	137.5
Silicious matter	3.84
Iron oxide, alumina and phosphates	0.17
Lime (CaO)	43.4
Magnesia (MgO)	12.2
Sulfates (SO_4)	18.5
Chlorides	9.0

COMPOSITION AND PREPARATION OF TEST SANDS.

The grading of the sands used in the tests was not predetermined. In combining the portions retained upon each sieve an effort was made not only to provide a range of gradings comparable with the usual gradings of natural sands, but also to include a few rather irregular or "freak" gradings. Table V gives the gradings of the test sands. Several of these gradings are shown graphically in Fig. 5.

Fig. 6, reproduced from photographs of the fractured surfaces of mortar cylinders, gives a general idea of the range of sand gradings used in the tests.

The grading of a test sand having been decided upon and the quantities of the component sizes having been computed and weighed, a uniform, composite sand was produced by hand mixing.

As previously mentioned, the sands used in concrete tests were not subdivided into their component sizes.

TEST SPECIMENS AND TESTING.

The test specimens made in connection with the various tests were as follows:

1. For the mortar consistency tests, standard briquettes only.

2. For the mortar strength tests, standard briquettes and cylinders 2 in. in diameter by 4 in. long.

TABLE V.—GRADING OF TEST SANDS.

Sieve Passed and Retained on.	Percentage Retained on Sieve.																
	Sand Letter.																
	A	B	C	D	E	F	G	H	I	J		L	M	N	O	P	Q
P 4 – R 8	15.0	25.0	5.0	25.0	0.0	10.0	30.0	0.0	0.0	8.0	10.0	15.0	8.0	14.0	11.0	11.0	9.5
P 8 – R 10	5.0	5.0	5.0	5.0	0.0	5.0	5.0	10.0	10.0	5.0	6.5	7.0	3.0	8.0	5.0	5.5	5.0
P 10 – R 20	25.0	23.0	15.0	15.0	0.0	18.0	30.0	25.0	25.0	22.0	16.0	22.0	11.5	21.0	16.0	18.0	19.0
P 20 – R 30	15.0	12.0	15.0	5.0	0.0	11.5	15.0	20.0	20.0	10.0	7.0	12.0	7.0	8.0	10.5	13.0	14.5
P 30 – R 40	15.0	15.0	15.0	5.0	0.0	18.0	10.0	15.0	15.0	14.0	16.5	14.0	10.5	12.5	15.5	16.0	20.5
P 40 – R 50	10.0	8.0	20.0	20.0	36.0	21.0	4.0	15.0	15.0	20.5	21.0	15.0	26.0	15.5	18.0	15.0	18.0
P 50 – R 80	10.0	8.0	20.0	20.0	52.0	15.0	4.0	10.0	10.0	20.0	21.5	13.0	32.0	19.0	20.0	15.5	12.0
P 80 – R 100	5.0	4.0	5.0	5.0	8.0	1.5	2.0	5.0	0.0	1.5	2.0	1.0	2.5	2.0	2.0	4.0	1.0
P 100	0.0	0.0	0.0	0.0	4.0	0.0	0.0	0.0	5.0	0.0	0.0	0.0	0.0	0.0	2.0	3.0	0.5
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	101.0	100.5	99.0	100.5	100.0	100.0	101.0	100.0

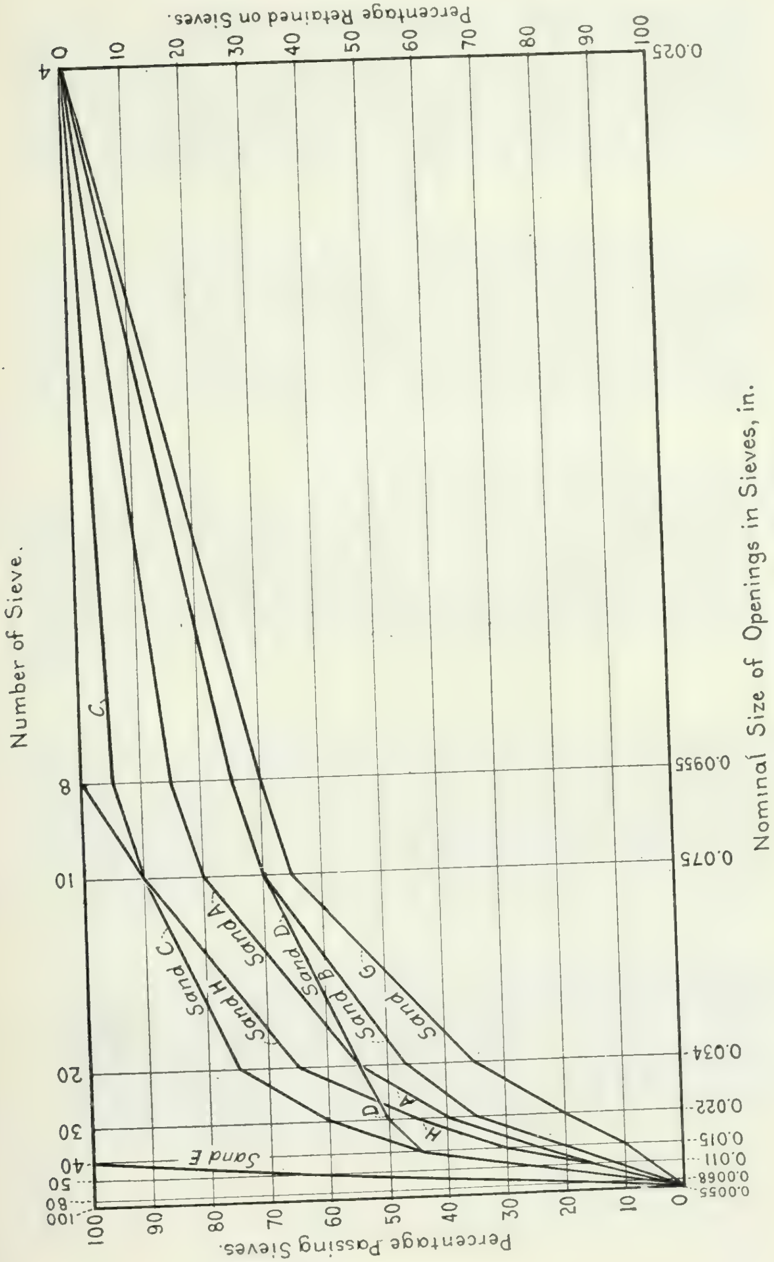
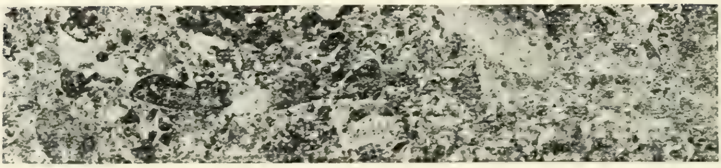
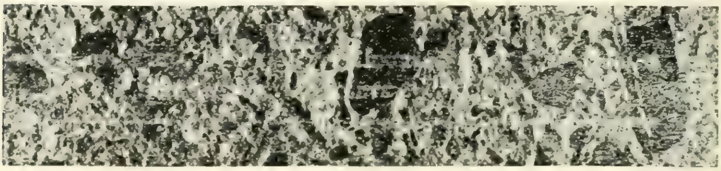


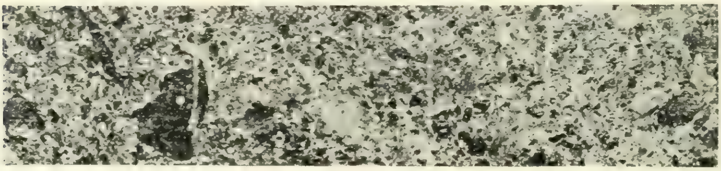
FIG. 5.—Grading of Test Sands.



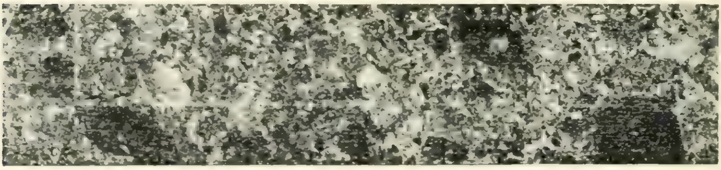
(*a*) Sand A.



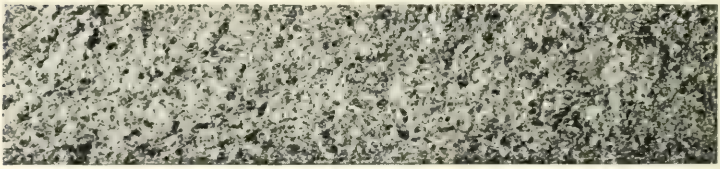
(*b*) Sand B.



(*c*) Sand C.



(*d*) Sand D.



(*e*) Sand E.

FIG. 6.—Texture of Mortars (×4).

3. For the concrete tests, cylinders 6 in. in diameter by 12 in. long, and from the mortar content of the excess concrete cylinders 2 in. in diameter by 4 in. long.

All test specimens of mortar consistency and mortar strength tests were tested at the municipal laboratory of the City of Toronto. All concrete test specimens and the mortar test specimens made in conjunction with them were tested at the testing laboratory of the Hydro-Electric Power Commission of Ontario, Toronto, Ont. In both laboratories the testing machines used were manufactured by the Tinius Olsen Testing Machine Co., Philadelphia, Pa.

In all compression tests a spherical seated bearing block was used and the ends of the specimens were bedded with sheets of beaver board to secure an even distribution of the load.

In all mortar tests, except the so-called "consistency tests," four 2-in. cylinders and four "standard" briquettes were tested at each age of 7, 30 and 60 days. Only briquettes were used in the mortar consistency tests. In the concrete tests five specimens were tested at each age.

For all tests the maximum load at ultimate failure was recorded.

PREPARATION OF TEST SPECIMENS.

In the preparation of test specimens a special effort was made to do the work with the greatest dispatch, consistent with the securing of uniform results. The mixing of the materials and the making of test specimens was the work of two operators.

Mortar Proportioning, Mixing and Molding.—Proportioning the cement content of a mortar in relation to the surface area of the sand used is in no way directly comparable with the commonly used method of proportioning by volume the quantities of cement and sand. A "standard" 1:3 Ottawa sand mortar, as used in cement testing, was computed to contain 1 g. cement to 13 sq. in. of surface area. This ratio or proportion was used in many of the tests.

The computed relation of the cement content to the surface areas of several sands assumed to be combined in mortars of 1:1½, 1:2, 1:2½, etc., mix by volume gave a suggestion as to the range of cement content to be used in tests intended to show the relation of strength to the surface area assumed to be covered per unit of weight of cement. This led to the adoption of the proportions, 1 g. cement to 10, 15, 20, and 25 sq. in. of surface area for such tests.

All mixing of mortar and molding of test specimens was in accord with the Standard Specifications and Tests for Portland Cement (C 9–17) and Tentative Specifications and Tests for Compressive Strength of Portland Cement Mortars (C 9–16 T) of this Society. The consistency of mix used was determined by special investigation. See "Mortar Consistency Tests."

Concrete Proportioning, Mixing and Placing.—The materials for concrete were proportioned as follows:

Cement, 21.12 lb. per 1000 sq. ft. of surface area of sand aggregate (1 g. cement to 15 sq. in. area). For the portion of sand passing a No. 100 sieve the surface area was assumed to be the same as that of an equal portion of material passing a No. 80 and retained upon a No. 100 sieve.

Sand and stone aggregates, 1 part sand to 2 parts stone by volume.

In order to secure greater uniformity these volumes were reduced to a unit weight basis. These unit weights were as follows:

1 cu. ft. sand	assumed at	100	lb.
1 " " stone	" "	87	"
1 " " water	" "	62.37	"

The water content of the mix was sufficient to produce a saturated, sticky, semi-plastic mortar showing no free water.

It will be noted in the above that in the proportioning of the cement content of the mix no account was taken of the surface area of the stone aggregate. At the time of making the test specimens the approximate areas of broken stone and gravel aggregates had not been determined.

The concrete was mixed by hand. The cement and sand were first incorporated to form a mixture of uniform color. Water was then added to form a mortar, into which the broken stone, after it had been surface moistened, was shoveled and the mixing of the entire mass continued until the particles of stone aggregate were thoroughly coated with mortar.

In the puddling of the concrete in the forms special attention was given to the uniform distribution of the broken stone and mortar. Bars having a diameter of $\frac{5}{16}$ to $\frac{3}{8}$ in., flattened to form a comparatively thin blade-like end, were used to secure this distribution. Compacting and the exclusion of entrapped air were mainly accomplished by lightly tapping the exterior surface of the forms with a wooden mallet.

From the excess concrete remaining from each batch after the 6-in. cylinder forms were filled, an amount of mortar sufficient to fill twelve 2-in. cylinder molds was secured. The larger stone particles of the concrete were removed by screening upon a $\frac{3}{8}$-in. screen.

The forms were removed from the test specimens 48 hours after filling. As soon as removed from the forms the concrete test specimens were marked for identification and placed in storage, where they were moistened three times per day by spraying, until required for testing. The mortar cylinders, upon their removal from the molds, were immersed in water.

MORTAR CONSISTENCY TESTS.

The marked influence of the consistency of the mix upon the ultimate strength of mortars renders it especially important that test mortars be made of uniform consistency. The importance of this investigation as a preliminary to the making of tests tending to prove or disprove the validity of the primary theory of the surface-area method of proportioning, is self-evident. Tests were therefore made with the object of developing a means of securing uniformity of consistency in accord with the secondary or consistency theory of this method of proportioning, that is—"The amount of water required to produce a normal, uniform consistency of mortar is a function of the cement and of the surface area of the sand aggregate to be wetted."

It is useless to even outline the preliminary tests made: suffice it to say that only trial or so-called "cut and fit" methods were found to be applicable. As a result of the preliminary tests it was found that "normal," uniform consistency mortars of varying cement content and of varying sand gradings were produced when the quantity of water used in the mix was made equal to (1) that required to reduce the cement to a normal consistency paste, plus (2) an amount equal to the surface area of the sand in square inches divided by 210, that is,

$$\text{Water (cc.)} = \left(\begin{array}{c}\text{Weight of cement (g.)} \times \text{Percentage required} \\ \text{to produce ``normal'' consistency paste}\end{array}\right) + \frac{\text{(Total surface area of sand (sq. in.).}}{210}$$

With a water content determined by the above equation each of the five test sands J, K, L, M, and N, described under heading "Composition and Preparation of Test Sands" (see Table V) was used in the preparation of two test mortars having cement contents proportioned 1 g. cement to 10 sq. in. sand area and 1 g. cement to 15 sq. in. sand area, respectively. The composition of these mortars is shown in Table VI. Standard briquettes for tension tests were made from each mortar. The strengths of these briquettes are shown in Fig. 7.

TABLE VI.—CONSISTENCY TESTS: COMPOSITION OF MORTARS.

Sand Letter.	Surface Area per 1000 g., sq. in.	Cement Content 1 g. : 10 sq. in.		Cement Content 1 g. : 15 sq. in.	
		Cement, g.	Water, cc.	Cement, g.	Water, cc.
J	7151	715.0	193.0	477.0	140.0
K	7301	730.0	197.5	487.0	143.5
L	5745	574.5	155.0	383.0	112.5
M	8811	881.0	238.0	587.5	172.5
N	6498	650.0	175.5	433.0	.127.5

MORTAR STRENGTH TESTS.

The means of securing a "normal," uniform mix having been determined, little difficulty was encountered in the preparation of test mortars intended to establish the efficacy of the primary theory of this method, namely: "The strength of mortar is primarily dependent upon the character of the bond existing between the individual particles of the sand aggregate. Upon the total surface area of these particles depends the quantity of cementing material."

Test mortars were prepared as follows:

1. A series of nine mortars composed of sands varying widely in their granulometric composition combined in each case with a quantity of cement proportioned in the relation: 1 g. cement to 13 sq. in. sand area.

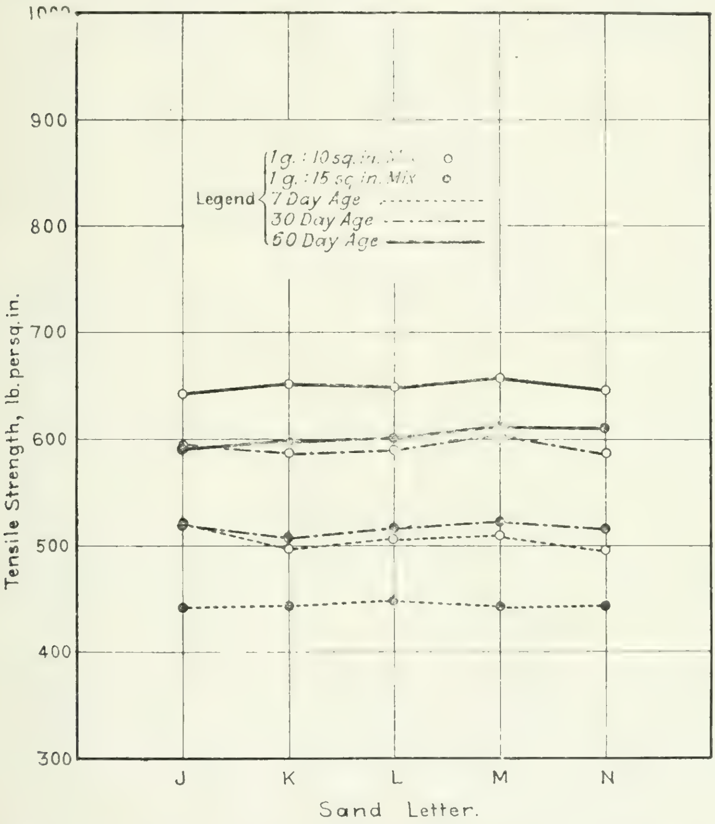


FIG. 7.—Consistency Tests—Tensile Strengths of Mortar Briquettes.

2. A series of four mortars composed of a sand of uniform granulometric composition combined in each case with quantities of cement proportioned in the relation: 1 g. cement to 10, 15, 20 and 25 sq. in. sand area, respectively.

3. A series of two mortars composed of the sands used in two of the concrete tests combined in each case with a quantity

of cement proportioned in the relation: 1 g. cement to 15 sq. in. sand area.

It is evident that, if the primary theory of this method of proportioning is correct, the ultimate strengths obtained from the first series of tests will be uniform and equal. It is equally evident that the relation of the ultimate strength to the cement content of the mortar is securable from the results of the second series. However, it must be borne in mind that the strengths obtained in each series are not necessarily the same as those which might be obtained from the use of a sand having its

TABLE VII.—STRENGTH TESTS: COMPOSITION OF MORTARS.

Sand Letter.	Surface Area per 1000 g., sq. in.	Cement, g.	Water, cc.	Ratio of Cement to Aggregate by Weight.
TEST SERIES NO. 1 CEMENT CONTENT—1 G. : 13 SQ. IN.				
A	5 856 6	450.5	128.0	1 : 2.22
B	5 106.1	392.0	111.5	1 : 2.55
C	7 683.7	591.0	168.0	1 : 1.69
D	6 758.4	520.0	148.0	1 : 1.92
E	12 816.4	986.0	280.5	1 : 1.12
F	6 769.1	521.0	148.0	1 : 1.92
G	4 182.0	321.5	91.5	1 : 3.11
H	6 564.6	505.0	143.5	1 : 1.98
I	6 564.6	505.0	143.5	1 : 1.98
TEST SERIES NO. 2 CEMENT CONTENT—1 G. : 10, 15, 20 AND 25 SQ. IN.				
F	6769	677.0	183.0	1 : 1.47
	6769	451.0	132.5	1 : 2.21
	6769	338.5	105.5	1 : 2.95
	6769	270.5	92.5	1 : 3.61
TEST SERIES NO. 3 CEMENT CONTENT—1 G. : 15 SQ. IN.				
O	7353.4	490.0	144.0	1 : 2.41
Q	6391.0	426.0	126.0	1 : 2.35

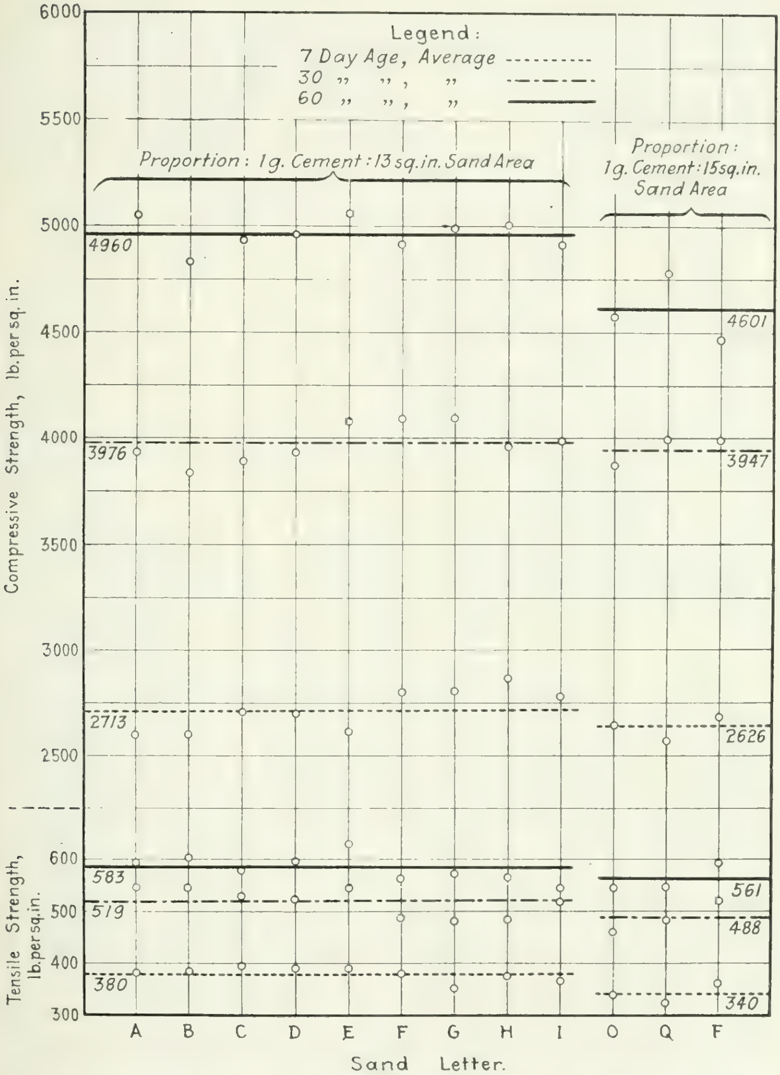


FIG. 8.—Strength Tests—Compressive Strengths of 2-in. Mortar Cylinders and Tensile Strengths of Mortar Briquettes.

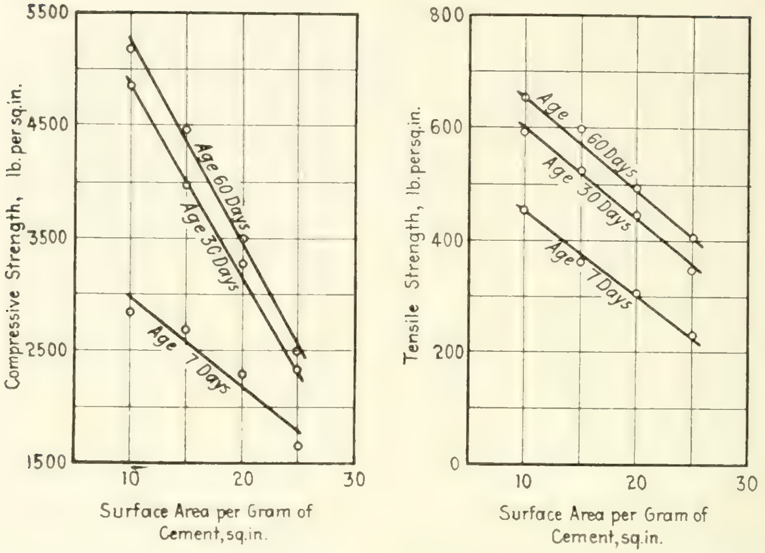


FIG. 9.—Strength Tests—Compressive Strengths of 2-in. Mortar Cylinders and Tensile Strengths of Mortar Briquettes; 1 g. Cement: 10, 15, 20 and 25 sq. in. Sand Area.

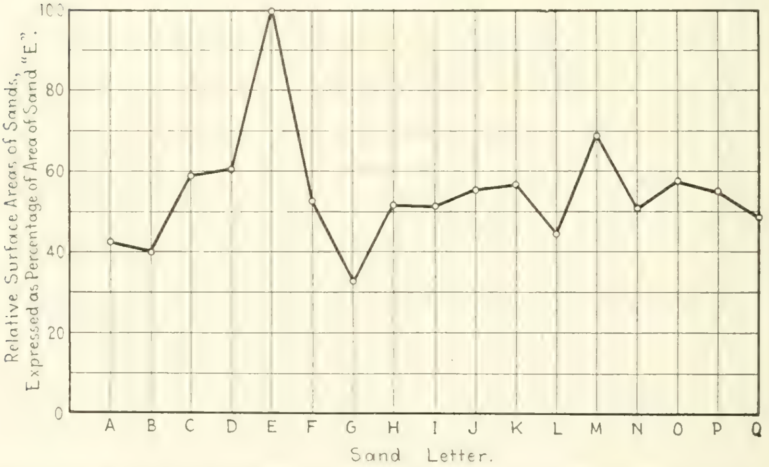


FIG. 10.—Relative Surface Areas of Sands (deduced from Tables VI and VII).

origin in a different rock material. The third series of tests provides a means of comparing the ultimate strengths obtained from mortars of normal consistency with those obtained from the mortar content of concretes forming a part of the general tests herein described.

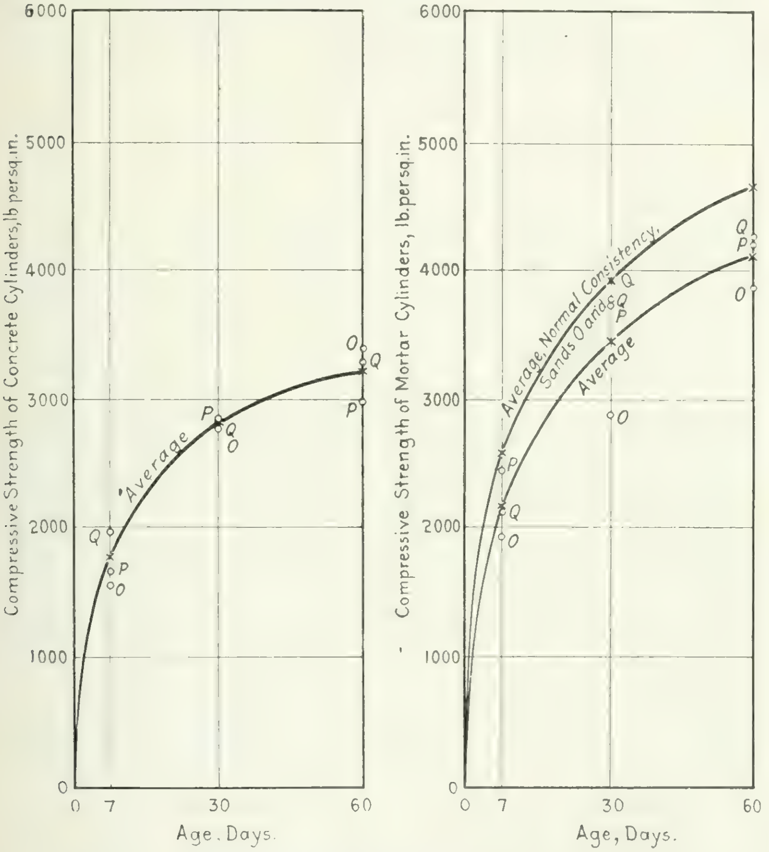


FIG. 11.—Compressive Strengths of Mortar and of Concrete Test Cylinders.

Table VII shows the composition of the test mortars of the three series described above. It also shows for each mortar the ratio existing between the cement content and the sand aggregate, by weight.

Fig. 8 shows the average ultimate compressive and tensile strengths obtained from test specimens of the first and third series, while Fig. 9 shows the results obtained from the specimens of the second series.

Fig. 10 was deduced from the information contained in Tables VI and VII. It shows by percentages the relation between the surface area of sand E and that of each of the other sands described in Table V. The economy of the surface-area method of proportioning is here apparent.

CONCRETE STRENGTH TESTS.

Fig. 11 shows the average strengths obtained from the tests of concretes and from the tests of mortars secured from the mortar portions of these concretes. For purposes of direct comparison, the average of strengths obtained from normal consistency mortars, sands O and Q, are also shown. In this connection a comparison with Fig. 13 is of interest.

The weaker strength of the concretes as compared with the mortars is doubtless due in part to the weakening effect of cleavage planes produced by the stone aggregate. A comparison of the strengths shown in Fig. 11 indicates a probability that by this method of proportioning, the relative values of sands for use in concretes can be determined from a comparison of mortars, the cement content of which bears a common ratio to the areas of the sands compared and the water content of which is the same as that to be used in the proposed concrete. The low strength of sand O mortar at an age of 30 days is probably due to the weakening effect of stone particles over $\frac{1}{4}$ in. in size contained in the mortar as a result of screening through a $\frac{3}{8}$-in. screen.

MISCELLANEOUS TESTS.

In connection with the foregoing tests three miscellaneous tests were made having an indirect relation to the results obtained therein. A description of these tests, together with the results obtained, follows.

Effect of Consistency of Mix upon the Strength of Mortars.—This test was undertaken with the object of securing information indicating the change of strength resulting from (1) the mixing, either by intent or by accident, of test mortars of too wet consistency, and (2) a variation of the water content of the mix from that required to produce a "normal" consistency mortar to that producing a "sloppy" mix, such as is frequently found in concretes of too wet consistency.

In each of these tests the relation of the cement content of the mix to the surface area of the sand aggregate was constant for each series; that is, for the first series a proportion 1 g. cement to 15 sq. in. sand area, and for the second series a proportion 1 g. cement to 10 sq. in. sand area. Sand Q was used in the first series and sand F in the second series.

TABLE VIII.—CONSISTENCY TESTS: COMPOSITION OF MORTARS.

TEST SERIES NO. 1c.
CEMENT CONTENT—1 G. : 15 SQ. IN.—SAND Q.

Consistency.	Surface Area per 1000 g., sq. in.	Cement, g.	Water, cc.	Percentage of Water to Cement and Sand.
Normal	6391	426	124	8.69
Medium	6391	426	136	9.54
Wet	6391	426	147	10.31

TEST SERIES NO. 2c.
CEMENT CONTENT—1 G. : 10 SQ. IN.—SAND F.

Consistency.	Surface Area per 1000 g., sq. in.	Cement, g.	Water, cc.	Percentage of Water to Cement and Sand.
Normal	6769	677	183	10.91
First	6769	677	217	12.94
Second	6769	677	251	14.97
Third	6769	677	285	16.99
Fourth	6769	677	319	19.02
Fifth	6769	677	353	21.05

Table VIII shows the compositions of the mortars and Figs. 12 and 13 show the average strengths obtained from test specimens for each series of tests.

Weight-Volume, Cement Paste Test.—This test was made as a check upon the common assumption that 110 lb. of dry cement produces 1 cu. ft. of cement paste. It was found that 2000 g. of cement when thoroughly mixed with 445 cc. of water (normal consistency) produces 1140 cc. of paste, corresponding to 109.52 lb. of dry cement to produce 1 cu. ft. of paste.

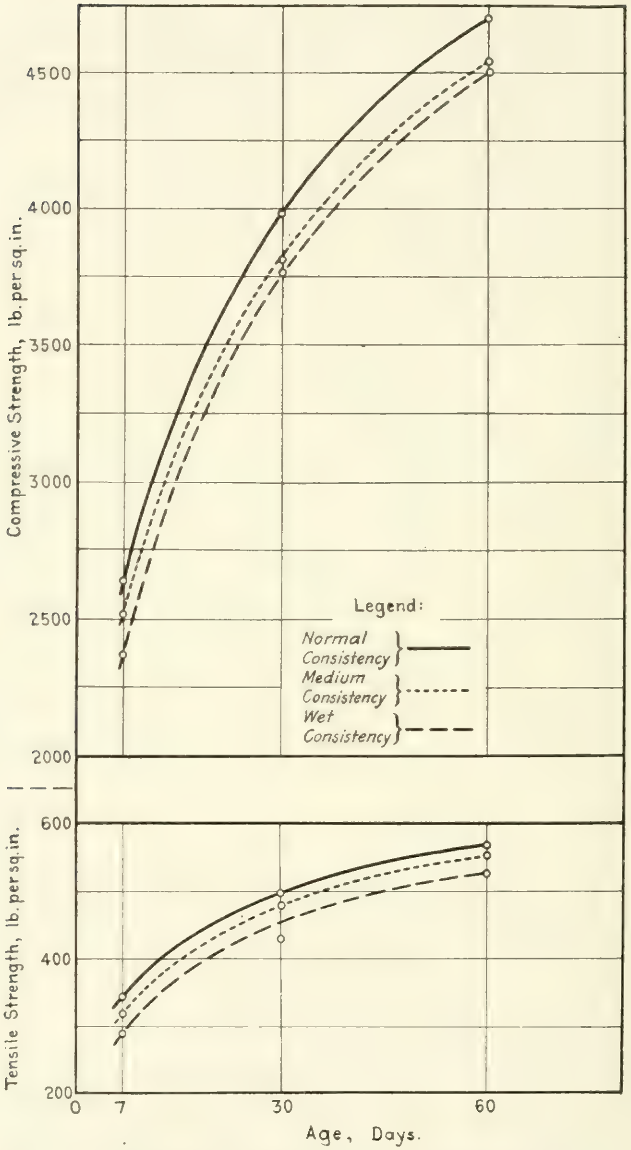


FIG. 12.—Strength of Mortars of Different Consistencies and Ages; Sand Q; 1 g. Cement : 15 sq. in. Sand Area.

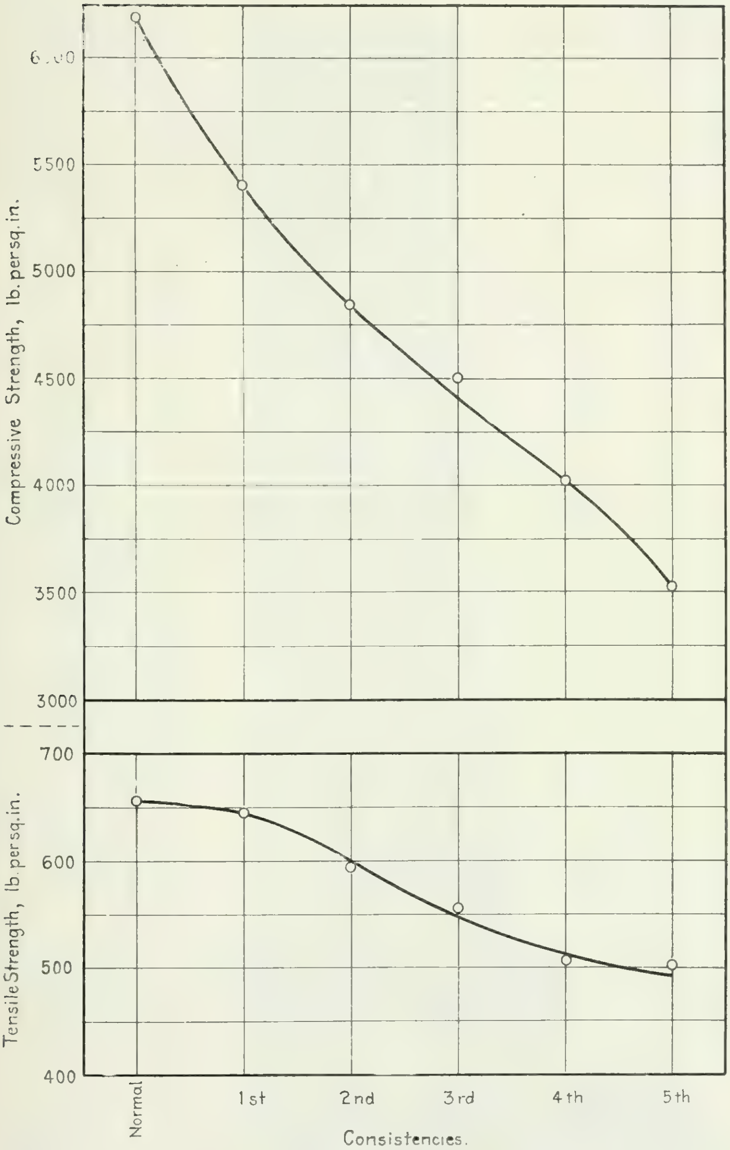


FIG. 13.—Strengths of Mortars of Different Consistencies, Age 60 Days; Sand F; 1 g. Cement; 10 sq. in. Sand Area.

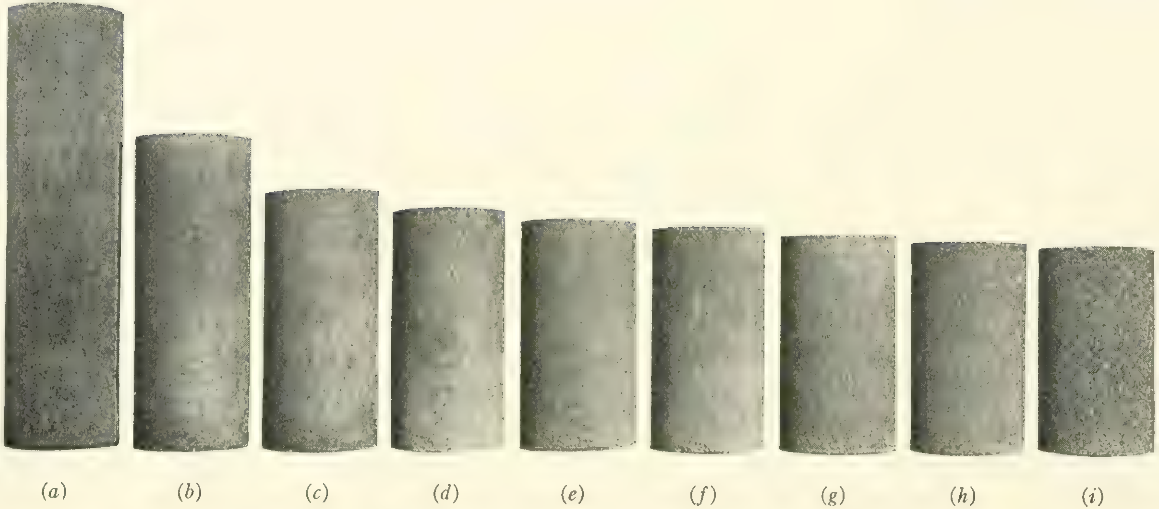


FIG. 14.—Mortar Cylinders in which the Cement Content was Decreased.

(*a*) 1 g. cement: 5 sq. in. Sand Area.
(*b*) 1 " " : 10 " " " "
(*c*) 1 " " : 15 " " " "
(*d*) 1 " " : 20 " " " "
(*e*) 1 " " : 25 " " " "
(*f*) 1 g. cement: 30 sq. in. Sand Area.
(*g*) 1 " " : 35 " " " "
(*h*) 1 " " : 40 " " " "
(*i*) Original Sand.

An increase of 35 cc. in the volume of water used produced an increase of 20 cc. in the volume of paste, which corresponds to a decrease of 2.11 lb. in the weight of dry cement required.

Bulking Effect of Cement Content of Mortars.—The bulking effect of the cement was especially noticeable in test mortars in which the granulometric composition or grading of the sands was such as to give comparatively large computed surface areas. Its variation with the proportion of cement used in relation to the surface area was also noted. Both conditions are in full accord with the primary principle of this method of proportioning.

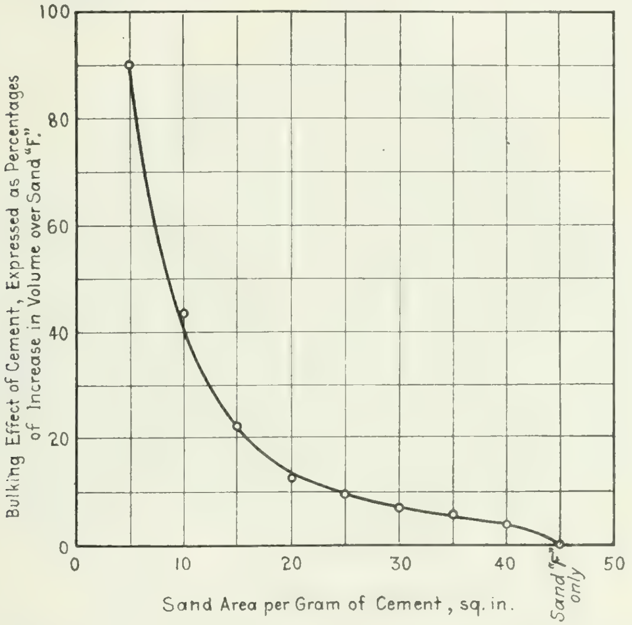


FIG. 15.—Relation of Cement Content to Bulk of Mortars—Sand F.

Fig. 14 shows a series of mortar cylinders in each of which 1200 g. of sand F were used and the cement content was successively decreased in the proportions:—1 g. cement to 5, 10, 15, 20, 25, 30, 35, and 40 sq. in., sand area. The cylinder at the extreme right-hand end of the series contains only a sufficient quantity of cement (15 g.) to retain the 1200 g. of sand in a cylindrical form, thus permitting a close comparison with the compacted bulk of the sand alone.

Fig. 15 shows the relative percentages of volume in relation to the volume of the "sand" cylinder above described.

In this connection it is of interest to note that the void in sand F was found to be 31.3 per cent. By the void method of proportioning the quantity of cement paste necessary to fill the void in 1200 g. of sand bulking 41.29 cu. in. would be 12.92 cu. in., requiring 374.3 g. of dry cement. With no allowance for the separating of the sand particles, this corresponds approximately to a cement content, 1 g. cement to 22 sq. in. sand area by the surface area method.

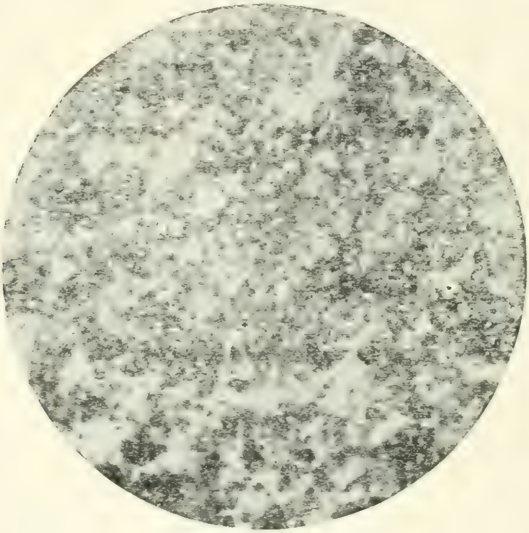


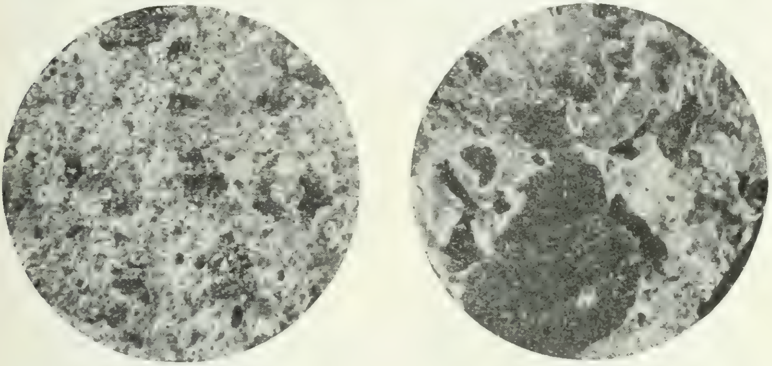
FIG. 16.—Texture of Fractured Surface of Neat Cement Briquette (×75).

Figs. 14 and 15 give no evidence of a marked change in the increment of increase of volume due to the cement content exceeding that of the void.

OBSERVED PHENOMENA OF TESTS.

Voids in Mortar.—Mortars produced under ordinary conditions invariably contain voids having two general sources of origin, namely: (1) those due to globule-like accumulations of water which evaporate, leaving so-called water voids, and (2) those due to air adhering to the surfaces of the sand particles or to air entrained during the mixing of the component materials, producing air voids.

Fig. 16 shows a photomicrograph (×75) of neat cement as it exists in standard briquettes. The effect of the surface tension of water is shown here by the great number of voids. This well-known attribute of water renders it impossible to secure, even in the richest mortars, an unbroken film of cementing material surrounding the particles of sand aggregate.



(*a*) Sand A. (*b*) Sand D.

FIG. 17.—Texture of Fractured Surfaces of Mortars, Proportioned 1 g. Cement: 13 sq. in. Sand Area (×20).

Resistance to Impact.—Hardness, toughness, etc., were roughly tested under the impact of hammer blows, "knob" ends of briquettes and fragments of broken cylinders being used for this purpose. Mortars having an equal cement content in relation to the surface area of the sand aggregate showed a most remarkable uniformity when tested in this rather crude way.

Texture of Mortars.—A careful microscopic examination of the cement matrix of the mortars containing test sands A to I, inclusive, proportioned as indicated in Table VII, showed, in all cases, an equal uniformity of distribution. In a comparison of mortars containing a less proportion of cement in relation to the surface area of the aggregate this condition was found to be equally true.

Fig. 17 shows photomicrographs (×20) of the fractured surfaces of mortars, proportioned 1 g. cement to 13 sq. in. sand area, in which the sands are of distinctly different granulometric composition.

Fig. 18 shows four photomicrographs (×20) of fractured surfaces of mortars varying in their cement content as follows: 1 g. cement to 5, 15, 25 and 35 sq. in. sand area. The specimens for photographing were taken from the mortar cylinders shown in Fig. 14. The decrease in the quantity of the cement matrix is readily recognizable by the decrease of matrix adhering to the particles of sand aggregate.

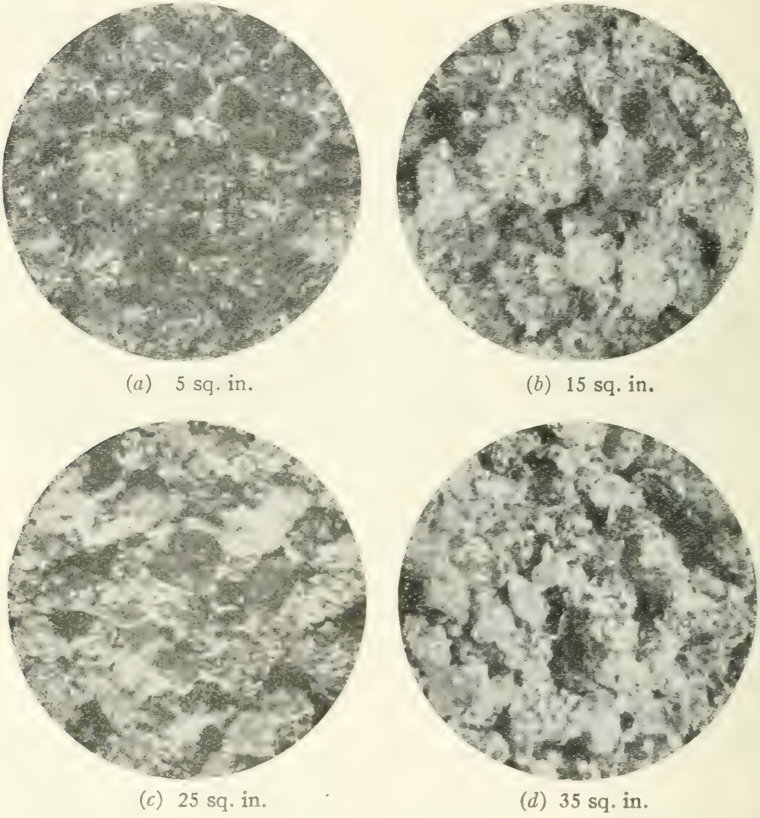

(*a*) 5 sq. in.
(*b*) 15 sq. in.
(*c*) 25 sq. in.
(*d*) 35 sq. in.

FIG. 18.—Texture of Fractured Surfaces of Mortars Proportioned 1 g. Cement: 5, 15, 25 and 35 sq. in. Sand Area (×20).

It is of special interest to note that although the first-mentioned mix contained, by weight, a greater quantity of cement than of sand aggregate and although the cement matrix may be said to "thoroughly envelop" the particles of the aggregate, it nevertheless contains myriads of minute voids which are probably of water origin.

Fig. 19 shows photomicrographs (×20, ×75) of "Ontario" brown sandstone. The comparatively small amount of cementing material holding the particles of sand in place is of special interest.

Effect of Excess Water.—The proper function of the water content of a mortar mix is to combine with the cement in producing the pasty matrix which, when set, binds the particles of the aggregate into a uniformly strong stone-like material. The addition of a comparatively small quantity of water in excess of that required for the fulfillment of its proper function produces a very marked effect upon the structure of the cement matrix.

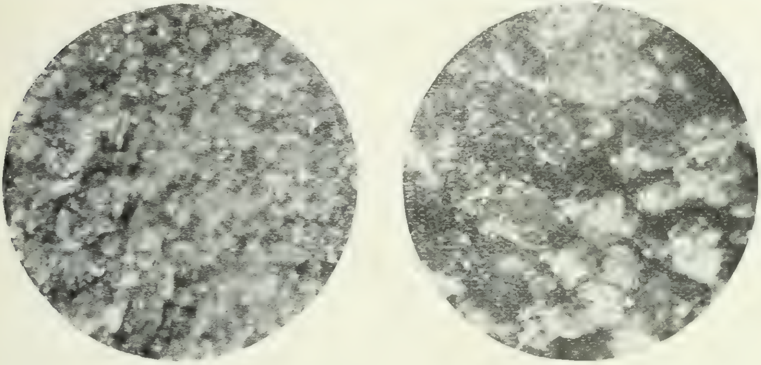

(*a*)× 20. (*b*)× 75.

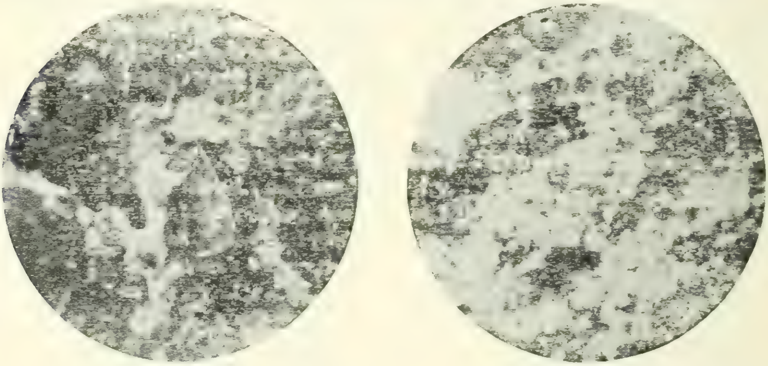
FIG. 19.—Texture of "Ontario" Brown Sandstone.

This change in the structure of the cement matrix can be readily seen by the aid of a microscope; but like sunlight it is far easier seen than described. However, in the miscroscopic examination of the fractured surface of a "normal" consistency specimen, say, at 50 to 75 diameters magnification, the observer takes special note of three conditions of the matrix, namely:

1. It is grayish in color.
2. It adheres to the particles of aggregate in amorphous, pasty appearing masses.
3. It contains myriads of minute voids, permeating the entire formation.

As compared with the above, the cement matrix of a "wet" consistency mortar specimen presents a radically changed appearance, that is:

1. Its color is changed from grayish to nearly a milky white.
2. It no longer adheres firmly to the surfaces of the aggregate, but instead appears as a comparatively loose, semi-crystallin formation which, although containing few, if any, real crystal forms, may be compared to rather loosely massed snow crystals.
3. It contains, when closely examined, comparatively few of the well defined globular-shaped voids observed in a "normal" specimen.



(*a*) "Normal" Consistency. (*b*) "Wet" Consistency.

FIG. 20.—Texture of Cement Matrix in Mortars of Different Consistencies (×75).

When examined under a lower magnification, say 16 to 25 diameters, the matrix of wet-consistency mortar specimens presents a loose, "sugary" or granular appearance. Doubtless this change in the physical structure of the matrix from a comparatively dense, compact material to an attenuated, fluffed up, skeleton-like mass lacking cohesiveness and other attributes of strength discloses the deep underlying but nevertheless primary cause contributing to the low strength, friability, shortness and other undesirable properties found in wet consistency mortars and concretes.

Fig. 20 shows photomicrographs (×75) of "normal" and of "wet" consistency mortar specimens. The latter specimen was produced from the mortar of the former by the addition of sufficient water to render it of a "mushy" rather than of a liquid consistency.

DESIGN VS. CONSTRUCTION.

Whether a structure be composed of mortar or of concrete, the ideal of its construction is that it shall fulfil the predetermined requirements of strength, durability, utility, etc., at the lowest cost; that is, other things being equal, economy and efficiency demand the development of the full value of the cement and of the aggregate. A large proportion of the structures now existing fall short of the ideal mainly for two reasons:

1. Not all of the factors influencing the strength, hardness, durability and other physical properties of mortars and concretes are known and have not, therefore, been given due consideration.

2. Infallibility is not an attribute of the human mind and in consequence defective structures are built, which like chains are no stronger than their weakest parts.

As regards strength alone there is a most remarkable lack of "team play" between the designer on the one hand and the construction superintendent on the other. This lack of coordination arises most commonly from the restricted field over which each may claim "I am monarch of all I survey." The average designer thinks in terms of pounds of compressive or of tensile stress rather than in terms of the materials to be used in the actual construction. Too frequently he clings tenaciously to the notion that a given mix will develop a given strength at an age of 28 days. For example, he assumes that a 1 : 2 : 4 mix proportioned by the commonly used volume method will develop a compressive strength of 2000 lb. per sq. in., while, as a matter of fact, the 1 : 2 : 4 mix actually used in the work he designs may attain a strength of from 1200 to 3000 lb. per sq. in. or over. He rarely realizes that in ordinary concretes of, say, 1 : 2 : 4 mix the actual cement content per cubic yard of finished concrete varies widely, due to the character and quality of the aggregates, to the consistency of the mix and to field methods and operations of mixing and placing. The average field superintendent commonly thinks in terms of bags and barrows, batches and bulks. He measures strength by the "ring" of the concrete under the blows of a hammer, which indicates that the form work can safely be removed. To him efficiency and excellence are gaged and measured not by ultimate results but by a day-to-day standard involving an intimate combination of time, volume and pay roll rather than by standards of strength, reliability and permanence.

The securing of greater uniformity in results approaching more closely the ideal, demands that a great amount of work be done—work not only of an educational but also of an experimental and creative kind—involving the training of the workman and of his foreman to a different conception of their duties, that they may become more expert and efficient; the consigning to a merited oblivion of time-honored practices and methods, unproductive of desired results; and the development and adoption of new methods and practices founded upon rational and scientific principles. This is indeed no menial task.

The maximum economy consistent with strength and durability will be realized when the designer can so proportion the several parts of a structure, that all will theoretically be worked to equal efficiencies, and those the maximum safe ones; and the superintendent of construction can so erect the structure as to conform to the conditions assumed in the design.

There is ample evidence that in order to bring mortars and concretes to the highest standards of excellence as structural materials our efforts must be directed more specifically toward the development of a more thorough knowledge of their component materials and the improvement of field methods and practices. The suggested investigation of available aggregates with a view to determining their values as materials for the making of mortars and concretes, preliminary to the designing of a proposed structure, properly deserves further consideration.

Extended examinations cannot economically be made in connection with structures of minor importance involving comparatively small total expense. In such cases a liberal use of cement is doubtless more economical. However, there should be a certain amount of investigation. The justification of expense in connection with structures of greater magnitude involving large quantities of mortar or of concrete materials is a quite different proposition when considered from an economic viewpoint. The results of the tests herein described give ample evidence of the economy of well-graded sands when used as aggregate for mortars and concretes proportioned in accordance with the surface-area method. It will frequently happen that such an investigation will involve only the collecting and testing of sample aggregates secured from commercial companies dealing in these materials. In other cases an investigation might involve a search for satisfactory sand and gravel deposits or for quarry sites.

It is an encouraging fact, and worthy of note in passing, that tests of aggregates are being regarded of much greater importance and are receiving correspondingly greater attention than formerly.

PRACTICAL APPLICATION OF THE METHOD.

The adaptation of the surface-area method of proportioning mortars and concretes to both laboratory investigations and to field construction operations presents no serious difficulties. The outstanding feature of this method, in so far as its practical application is concerned, is the importance of knowing the granulometric composition of the aggregates. It must be admitted that the securing of this all-important information involves a comparatively small amount of labor, and by way of equipment the use of only the necessary scales, standard sieves and screens. The time element involved is comparatively negligible, since as described more fully herein the computation work of determining areas and quantities of cement can be largely reduced to the most simple mathematical operations by the use of tables and diagrams. For use in the laboratory and in the field, diagrams drawn to a large scale increase accuracy and reduce labor.

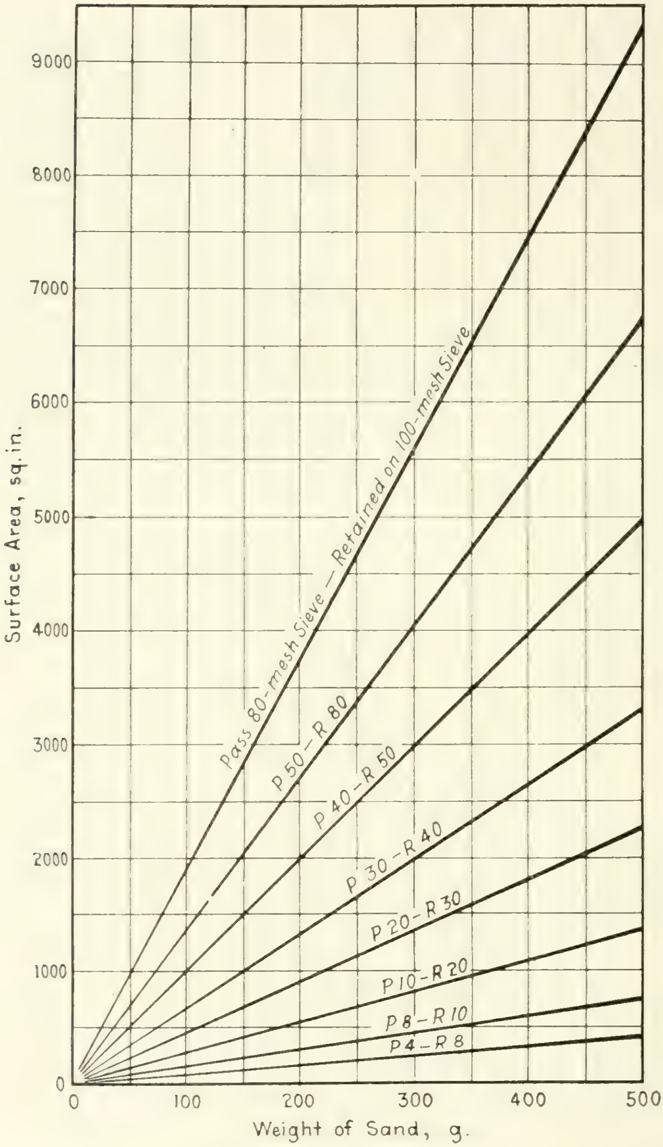


FIG. 21.—Surface Areas (sq. in.) corresponding to Various Weights of Sand Aggregate (g.).

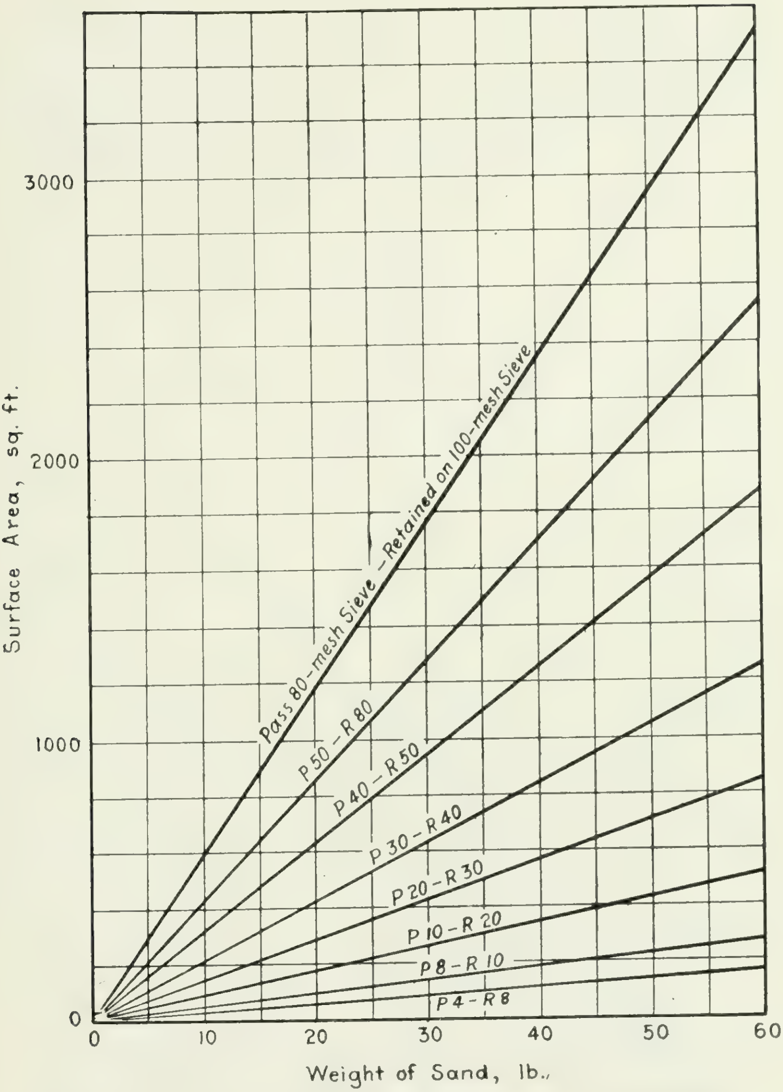


FIG. 22.—Surface Area (sq. ft.) corresponding to Various Weights of Sand Aggregate (lb.).

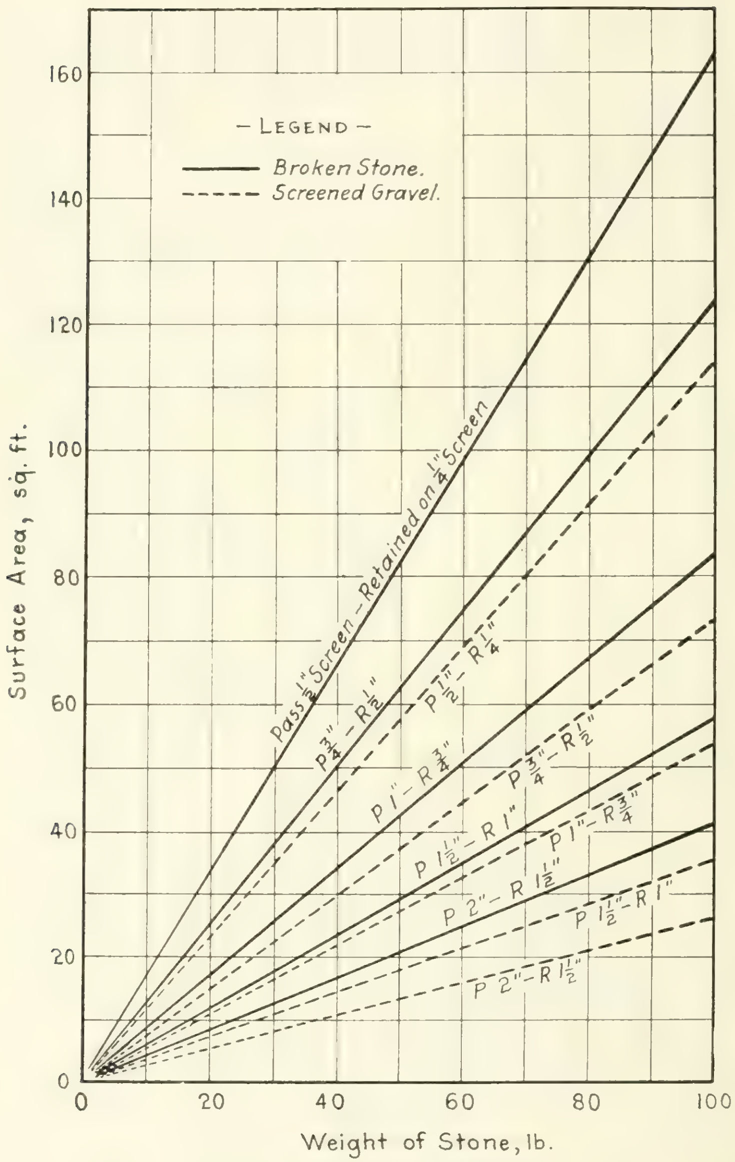


FIG. 23.—Surface Area (sq. ft.) corresponding to Various Weights of Stone Aggregate (lb.).

Figs. 21 and 22 are designed for use in determining the surface areas of sand aggregate. The former is intended for laboratory use and the latter for both laboratory and field use. These diagrams are derived from information contained in Table III.

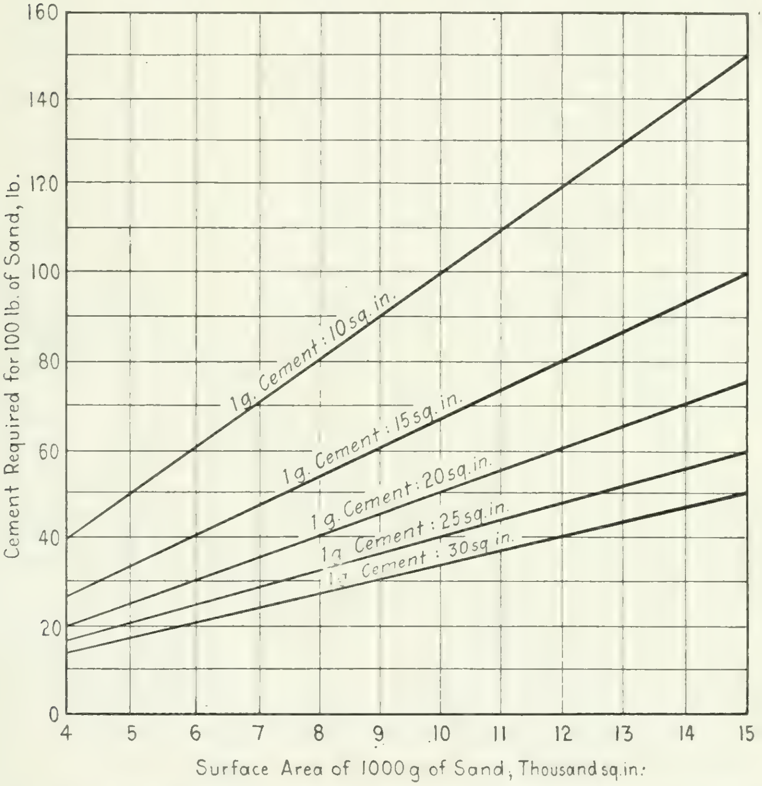


FIG. 24.—Weights of Cement (lb.) per 100 lb. of Sand Aggregate corresponding to Various Surface Areas per 1000 g. of Sand Aggregate and Various Proportions of Cement to Surface Area.

Fig. 23 is designed for use in determining the surface area of stone aggregate and is intended for both field and laboratory use.

Fig. 24 shows a conversion diagram for determining the relative quantity of cement in pounds per 100 lb. of sand from the corresponding relation of cement in grams to the surface area of 1000 g. of sand and vice versa.

Fig. 25 shows a conversion curve for determining the quantity of cement in pounds per 100 sq. ft. of surface area of aggregates which corresponds to the relation of 1 gram of cement to any desired surface area of aggregates in square inches and vice versa.

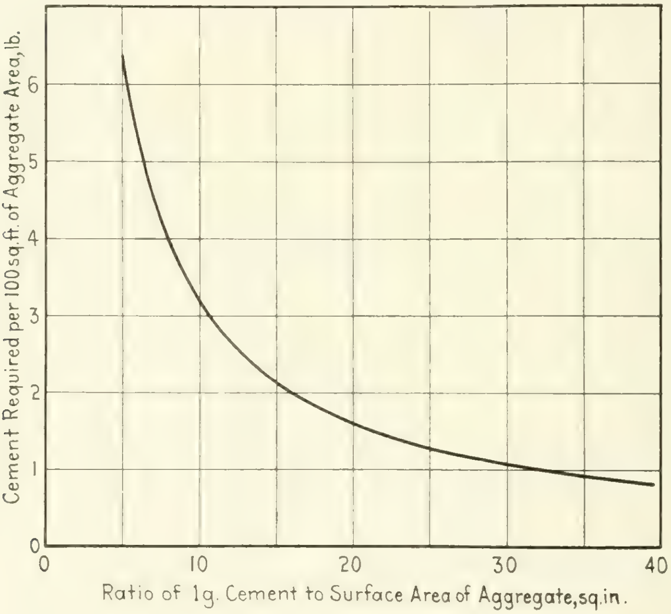


FIG. 25.—Curve for Converting Surface Area per Gram of Cement into Pounds of Cement per 100 sq. ft. of Surface Area.

Use of Diagrams.—The following examples explain the method of using the diagrams shown in Figs. 21 to 25, inclusive:

Example No. 1.—Required to find the composition of a batch of mortar using 1000 g. of sand A and a cement content proportioned: 1 g. cement to 15 sq. in. sand area.

Sand Area.

Sieve.	Grading, per cent.	Weight, g.	Area (Fig. 21), sq. in.
P 4 – R 8	15.0	150	142
P 8 – R 10	5.0	50	75
P 10 – R 20	25.0	250	694
P 20 – R 30	15.0	150	676
P 30 – R 40	15.0	150	997
P 40 – R 50	10.0	100	992
P 50 – R 80	10.0	100	1 348
P 80 – R 100	5.0	50	932
Totals	100.0	1 000	5 856

$$\text{Cement (g.)} = \frac{5856}{15} = 390.5.$$

$$\text{Water (cc.)} = \left\{ 390.5 \times 22.25 \text{ per cent (normal consistency)} \right\} + \frac{5856}{210} = 115.$$

Example No. 2.—Required to find the composition ot a batch of concrete using 100 lb. of sand *A*, 200 lb. of broken stone graded as shown below, and a cement content proportioned: 1 g. cement to 15 sq. in. aggregate area.

The area of the sand aggregate is determined as shown in Example No. 1 except that Fig. 22 is used, therefore: Sand area (sq. ft.) = 1845 sq. ft. per 100 lb.

Stone Area.

Screen.	Grading, per cent.	Weight, lb.	Area (Fig. 23), sq. ft.
P 1½ in. – R 1 in	60.0	120	69.0
P 1 in. – R ¾ in	25.0	50	41.5
P ¾ in. – R ½ in	10.0	20	24.5
P ½ in. – R ¼ in	5.0	10	16.0
Totals	100.0	200	151.0

Total area of aggregates = 1996 sq. ft.

Cement (lb.) = 19.96 x 2.11 (Fig. 25) = 42.12 lb.

PRACTICAL LIMITATIONS.

It is especially important to note that in its application the surface-area method of proportioning admits of certain physical limitations. The more important of these are here discussed briefly.

Effect of Dust.—The effect upon the physical properties of mortars and concretes of a sandy "dust" passing a No. 100

sieve is not definitely known. The main feature to be considered in this connection is the relation of the sizes of the "dust" particles to the sizes of the cement particles. A microscopic examination of the cement used in the tests described in this paper showed the sizes of the greater portion of the cement particles to range from 1.5 to 3.3 μ.[1] in their largest dimensions with an average dimension of approximately 2.2 μ., that is, $\frac{1}{11,540}$ in. Some of the larger particles measured ranged in size up to 6.7 μ.

Disregarding entirely the effect of the surface tension of the water used in the mix, it is reasonable to assume that the particles of dust do not become "coated" with cement paste, but that instead they become linked to adjoining particles of aggregate by one or more separate cement bonds. Doubtless the cohesion existing between particles of cement is greater than the adhesion existing between these particles and the particles of dust or other aggregate. It follows, therefore, that the strength of the mass must be somewhat weakened by the inclusion of dust in the aggregate.

Laboratory vs. Field.—The most important difference between the preparation of mortars in the laboratory and the field is found in the methods of mixing. In the laboratory the operator submits the mix to a thorough kneading and squeezing which forces the component materials into the closest possible contact with each other. In the field the mixing and frequently much of the work of transporting and placing tends to separate and break up rather than to knead and compact the mortar mass.

Field construction conditions are never ideal, even when carried on under the most careful supervision. In consequence, the strengths and other physical properties of field-made mortars and concretes frequently differ widely from the results obtained by tests made in the laboratory, in accordance with standard laboratory practice, with the object of obtaining a measure of the constructive value of the materials.

Coarse vs. Fine Sands.—Mortars in which the sand aggregate contains a comparatively large proportion of coarse particles are subject, during mixing and placing operations in the field, to an intensified movement of the water content which tends to produce an improper distribution of the cement. This condition is most noticeable in concreting operations.

---

[1] One micron (μ) = $\frac{1}{25390}$ in.

When mixed to "normal" consistency, so-called well-graded sands do not produce mortars which are as "workable" as those in which the sand aggregate contains larger percentages of smaller sized particles.

As compared with mortars containing well-graded sand aggregate, mortars containing aggregates composed entirely of fine particles must be subjected to a greater amount of mixing in order to secure a uniform distribution of the cement by a thorough abrasion which will separate the fine particles of aggregate tending to cling together.

Wet vs. Dry Sand.—The amount of moisture existing in the sand aggregate constitutes one of the most commonly disregarded sources of variation in the strength of field-made mortars and concretes. Various tests have shown that the surface tension of the water film enveloping the sand particles holds the particles apart, thus producing a decided increase in the gross volume. Sands made up of fine particles, and in consequence having greater surface area, increase more in volume than coarse sands. It is evident that a disregard for this important factor may produce materials the ultimate strengths of which are quite different from those contemplated in the design.

CONCLUSIONS.

From a careful consideration of the results obtained and of the phenomena observed in the tests described in this paper the following conclusions appear to be warranted:

GENERAL.

1. The claim that the surface-area method of proportioning the cement content of mortars and of concretes is essentially scientific and rational is proven by the uniformity of results obtained in comparative strength tests of mortars and concretes and by the phenomena observed in these tests.

2. With a given uniform proportion of cement in relation

to the surface areas involved, this method provides a definite and practical means of comparing the relative strength-producing qualities of aggregates of varying physical, chemical and mechanical properties.

3. This method provides a means for a more thorough investigation of the functions of sand and stone aggregates and for a more complete development of the true values of all the component materials of mortars and concretes.

4. Excess water in an over-saturated mortar or concrete mix exerts a decidedly weakening effect upon the cement matrix by producing a change in the physical structure of the matrix which tends to destroy the cohesion existing between the particles of cement and the adhesion existing between the cement and the aggregate.

5. In a normal consistency mortar the relation of the area of the particles of the sand aggregate to the cement content of the mix determines the strength of the mortar, provided the strength of the sand material is greater than that of the cement matrix. A similar condition applies to concrete mixes not over-saturated.

MORTAR.

6. The strengths of mortars containing a given cement and sand but varying for the different mixes in the proportions of these ingredients, are directly proportional to the relation existing between the cement content and the surface area of the aggregate. It follows, therefore, that the strength of a mortar of given mix being known, the mix of a mortar having a desired strength can be pre-determined for the same materials.

7. The quantity of water required to produce "normal," uniform consistency mortars from a given cement combined in varying proportions with sands having the same origin but varying in their granulometric composition, is a function of the water required to reduce the cement to a "normal" paste and the surface area of the sand particles to be wetted.

8. The increase of volume due to the mingling of varying quantities of cement particles with a uniform quantity of a given sand bears no apparent relation to and is evidently not dependent upon the void in the sand.

CONCRETE.

9. The tests indicate a probable definite relation between the ultimate compressive strength of the mortar content and the ultimate compressive strength of the concrete when the test specimens of the former are produced from mortar of the same mix and consistency as that used in the concrete.

Acknowledgements.—The author takes sincere pleasure in here giving due credit to J. S. Burgoyne, A. S. Goss, R. G. Goss, W. G. Howse, H. W. McAll, F. G. Marriott, and C. E. Stilson, who have rendered worthy assistance in the making of test specimens, chemical and physical tests and photographs, and in the tabulation of data.

DISCUSSION.

Mr. Johnson. MR. NATHAN C. JOHNSON.—This paper, showing so much thoughtful and patient preparation, has been of special interest to the speaker, inasmuch as Mr. Edwards has been carrying on studies correlating tests on physical strength obtained under varying conditions with internal structures as revealed by optical examination. The speaker has been doing similar work for a number of years and to date has classified over 4000 photographs relating to the examination of some 1600 concretes of known composition, conditions of manufacture and curing. Whether or not these or other studies will ultimately admit of such classification as to establish a science in concretes analogous to the optical examination of metals is as yet in doubt. But it would be unwarranted to say that this may not eventually be done.

Optical examination already possesses considerable practical value for certain purposes. As an instance, it may properly be mentioned that by these means it has been possible, by taking an extensive series of borings from a defective structure, to make evident the procedures in force from day to day during the building; to localize within narrow limits the defective portions of the structure; and to correlate them with the procedures indulged and the materials used in each section. The diagnosis made in this way has proven surprisingly exact by comparison with construction photographs and the evidence of inspectors who watched the work. Strength and other tests have also been correlated with this photographic work and a large amount of valuable data has been obtained. In expert hands, optical studies of concretes are even now of value, with probabilities for much greater value as classification and study progresses. In other hands, however, or by misinterpretation of the characteristics of small areas under high magnification, wholly erroneous conclusions will be reached.

The method advanced by Mr. Edwards as to proportioning by surface areas seems to the speaker unnecessarily cumbersome. Areas of particles are direct functions of their mean

Mr. Johnson. diameters; and mean diameters may be expressed in terms of sieve openings. Mechanical analyses, therefore, when properly interpreted, possess all necessary data without secondary computation of areas.

The cohesive medium in all mortars and concretes is a product formed by union of cement and water. Abrams has expressed in a formula the effect of greater or less dilution of this product by requirements of any given aggregates as to water. Cementing product per sand grain is therefore the determinator of strength.

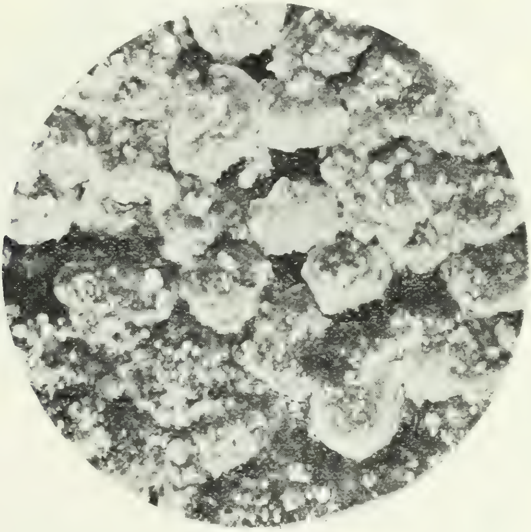


FIG. 1.—Cement Particles and Sand Grains, 1 : 3 Mortar. (× 20.)

To illustrate, it is impossible that cement particles should "cover" sand grains, in spite of the common expression to this effect. Cement particles at time of mixing touch sand grains only at points of tangency. (Figs. 1 and 2.) Contacting of sand and cement therefore depends upon diffusion in solution. For this reason, if for no other, proportioning by areas is deceptive.

"Particles of cement per sand particle" is, however, a critical ratio; and this ratio also takes account of quantity of

Mr. Johnson. water required for plasticity. For some time past, the writer has been making mathematical investigations of the published test results of others, with the result that considerable additional information as to the behavior and constitution of concretes has been obtained.

Applying a variation of this method to four sands, A, C, D and G, used by Mr. Edwards, it is found that in a cubic yard of 1 : 3 mortar there would be in round figures, and allowing 30 per cent voids for each sand, the following number of particles:

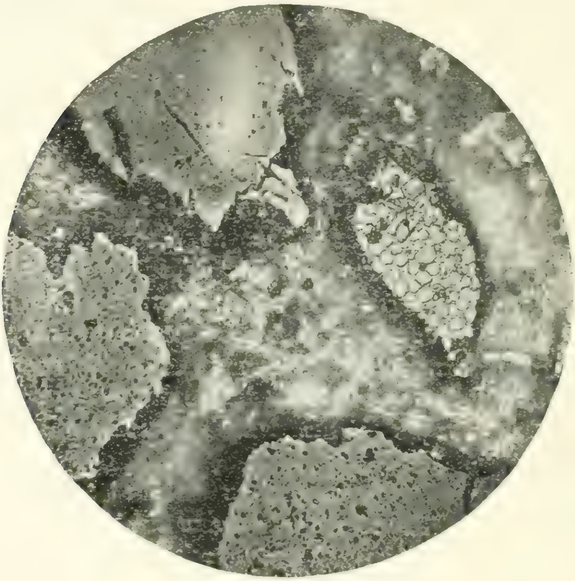


FIG. 2.—Irregularities of Surfaces of Sand Grains.
(× 200.)

A	C	D	G
109 000 000 000	199 000 000 000	198 000 000 000	97 000 000 000

In these mortars, there would be about 240,000,000,000 cement particles; and water in quantity commensurate to the number of sand particles. Allowing, for the sake of argument, an error of one or two billion particles in any or all of the above computations, the physical mixing of these substances is seen,

Mr. Johnson

perhaps more clearly than by other methods, to be a tremendous physical undertaking as well as one of vital importance. The number of stone particles in a concrete is relatively unimportant.

Granting the correctness of these figures, the "cement per grain" ratio is found to be:

A	C	D	G
2.2 : 1	1.2 : 1	1.21 : 1	2.48 : 1

These contrasts in sands and the effects of varying gradings are here forcefully evident. Considering further the dilution through extra water required by the finer sands, it becomes a matter for wonder, not that some concretes are below acceptable grade, but rather that they stand up under the stress of their own weight.

It is to be regretted that strength test data were not available in this paper to make the effect of these factors more evident. Grain factors as above may be established directly from a simple equation based on mechanical analysis; and the study of strengths in the same manner as before noted teaches how a desired strength may be approximated. It is hoped to publish these data in the near future, as they offer considerable advantages in simplicity of method.

Mr. Edwards speaks of wet versus dry sand in connection with surface tension.[1] Unless the speaker misunderstands Mr. Edwards, this is a misconception of the action of surface tension. In spite of many assertions to the contrary, surface tension plays an important part in all mixing operations. It is surface tension against air which gives to wetted sands or to mortars their consistency. It is surface tension which permits their retention of shape after deformation; and on a larger scale it is surface tension which makes the mixing of relatively dry mortars or concretes so difficult. Inside the water envelope, of whatever size it may be, surface tension is not in play provided there is no occlusion of air at irregularities on the surfaces of the particles. That is to say, once particles are thoroughly wetted, surface tension is not evidenced within the fluid, in the absence of retained gaseous bubbles. The dispersion of sand by moisture cited by Mr. Edwards is more

---

[1] See p. 281.—Ed.

Mr. Johnson. properly the occupancy of space by a volume of water surrounding a particle rather than any manifestation of surface tension. Furthermore, the action of surface tension would be to compact the particles rather than to disperse them. Except for the probable importance of surface tension when eventually understood, controlled and utilized, this correction would be of no moment.

The Chairman. THE CHAIRMAN (MR. ROBERT W. LESLEY).—Mr. Edwards' paper is very interesting. I am reminded of a statement which I made in a somewhat off-hand way, in discussing this subject from a different viewpoint just before this meeting, that the making of a good concrete was rather a question of paint; that is, the cement and water, corresponding respectively to the coloring matter and oil of the paint, form a "paint" with which the sand is painted; then the sand forms a mortar with which the stone is painted; and concrete is the result of that painting operation. This thought may possibly be worthy of some investigation.

Mr. Goldbeck. MR. A. T. GOLDBECK.—About four years ago the speaker had it impressed upon him very forcibly that some test should be developed that would permit of determining the concrete-making properties of sand, almost as soon as the sample arrived at the laboratory. When a concrete construction is in progress there are often occasions when the sand must be used as soon as it arrives, or else the work must stop. The period between the time the sand is delivered and when the 7-day strength test falls due is too long from the contractor's and from the constructing engineer's point of view.

At the Philadelphia Municipal Laboratory, a large number of sands are tested and an effort was made to study the tabulated results of these tests in order to see if some relation could not be discovered between the strength tests and other physical properties. A study of the mechanical analyses looked rather hopeless in view of the wide range in grading of sands having about the same strength. A little theorizing, however, showed that there must be some relation between the surface area of the grains of sand, which in mortar are coated by cement, and the strength of the mortar. The greater the surface area, the more cement will be required to coat the grains. Surface

Mr. Goldbeck. area is dependent on the size of the grains and their shape, so that knowing the mechanical analysis of any given sand, the superficial area of the grains in a given quantity is readily approximated. The grains were assumed as spheres, and the sieve openings were assumed equal to those of the average commercial sieves. The refinement adopted by Mr. Edwards, that of counting the grains in a given quantity of sand, was not used, but a more approximate method of obtaining the area was employed. It is my recollection that the areas indicated in the accompanying curve (Fig. 3) were obtained on the basis of the mean of the minimum and maximum diameters between the various sieves used.

Referring to the curve shown in Fig. 3, it will be seen that the results lie in a belt which shows a very decided relation between strength ratio and superficial area. It was found necessary to leave out of consideration the particles finer than the No. 100 sieve in establishing this relation. These particles are of about the same size as the cement particles, and probably aid in coating the larger particles. The results recorded are based on two briquettes each, and extend over several years. It is very probable that if more briquettes had been available the relation between surface area and strength would have been even more marked.

Like Mr. Edwards we also developed a formula for the percentage of mixing water to be used in gaging a 1 : 3 mixture of the cement and sand to the same consistency as Ottawa sand mortar. Without going into detail regarding its development, the formula is as follows:

$$\text{Percentage of water} = P\,N + \frac{1.15A}{3200}\,(n - P\,N),$$

in which P = percentage of cement and sand particles finer than No. 80 in the mix, N = normal consistency of neat cement, A = area of 100 g. of sand in square centimeters including only material coarser than No. 80, and n = normal consistency of Ottawa sand mortar.

The constant 3200 is the area of 100 g. of Ottawa sand, and 1.15 is used to take care of the fact that most sands tested are more or less angular and have larger area than spherical grains. The first term PN represents the quantity of water

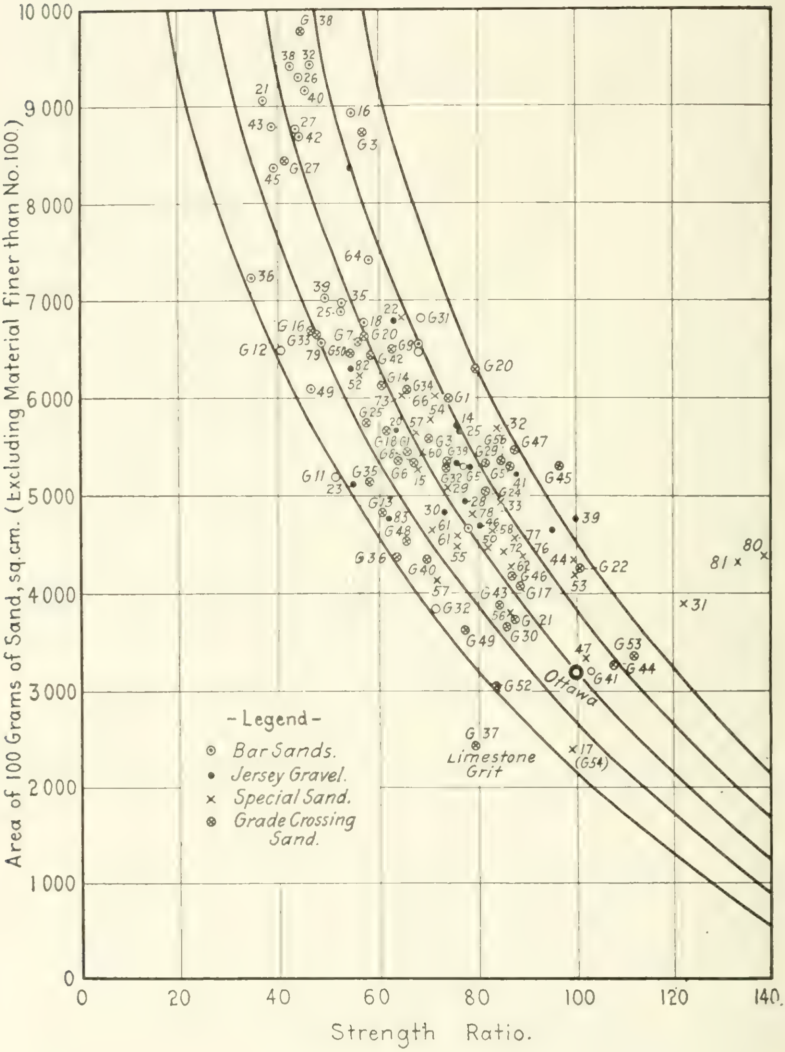


FIG. 3.—Curves showing the Relation between Surface Areas of Sands and Mortar Strengths.

Mr. Goldbeck. required to gage the cement in the 1 : 3 mortar to normal consistency. The quantity in parenthesis $(n-PN)$ is the percentage of water in excess of that required to gage the cement in a 1 : 3 Ottawa sand mortar to normal consistency. This excess is needed to wet the surface of the sand grains and the finer the sand and the greater its superficial area, the greater must be this excess quantity of water in order to gage it to the same consistency as Ottawa sand mortar. This fact accounts for the quantity $\frac{1.15A}{3200}$, which represents the ratio of the area of the sand under investigation to Ottawa sand. Although this formula gave very good results for most sand, there were exceptions particularly when the sand had a large amount of fine material. It is believed that a little more investigation would permit of altering the formula to make it generally applicable to all sands.

In the laboratory we often estimated the strength ratio on the basis of the superficial area theory, and when the 7-day strength tests fell due we compared our estimate with the strength results. The curve in Fig. 3 best shows how closely we could predetermine the strength ratio. Most of the results lie within 10 per cent of the average, while some were between 10 and 20 per cent from the average curve upon which we based our predictions. The character of the sand due to its source influences these predictions, and causes a wider variation from the average than would be the case if sands all from the same source of supply had been used.

Mr. Talbot. MR. A. N. TALBOT.—I cannot help expressing the personal opinion that Mr. Edwards has given us something to think about. There is evidently an element of interest in surface areas which may help to explain some of the things we have been wondering about. We have still much to learn about the elements which contribute to the properties of concrete. Concrete is certainly a very complicated material, and a variety of contributing agencies combine to make its strength and other properties. No one agency by itself will explain results. The amount of water used has been named as an important element in the control of strength; but it is not the only one. It is quite possible that calculations of surfaces may finally

Mr. Talbot. help in explaining the effect of an excess of water, and possibly also a consideration of surface areas will have an influence in determining how we may do something in the future to make concrete without so much water and yet get the consistency which is advantageous when the concrete is put into the work.

Mr. Abrams. MR. D. A. ABRAMS.—It is very interesting to note the experience of the men here this evening relative to the effect of size and grading of concrete aggregates. This problem has also been under consideration in the experimental work being carried out under the speaker's direction through the cooperation of the Portland Cement Association and the Lewis Institute in Chicago. Our studies of the effect of size and grading of aggregates were begun about three years ago. We had in the laboratory at that time the results of tests on mortars from about a thousand different sands from all parts of the United States. We undertook to study these tests in order to determine if possible the influence of the grading of the sand on the strength of the mortar. It seemed that this mass of data must contain some clue as to the nature of this relation. This study was begun by plotting the relation between the mortar strength and the amount of material in the mortar finer than the 100-mesh sieve. This gave no satisfactory result. We then made a similar study based on the material finer than the 50-mesh sieve, etc. Studies based on no single sieve in the series gave us any desired information. However, it occurred to us that instead of basing our studies on the amount of materials finer than each individual sieve, we should add up the percentages and make a study of the totals secured in this way. When this was done, we found a very definite relation between the grading of the particles and the strength of the mortar. These mortar tests, you will understand, were made over a period of several years, using different lots of cement, and under conditions varying in many respects.

The function derived by adding up these percentages we called the fineness modulus of the aggregate. I shall not have time now to go into a discussion of the method of calculating this modulus or of its many interesting applications to the study of concrete and concrete aggregates.

Mr. Abrams. The fineness modulus is simply a yardstick whereby the grading of the aggregate can be measured. The grading of any granular material can be measured in the same way. The method is very simple, and involves nothing more than adding a series of terms in which the sieve analysis of the aggregate is expressed. We short-circuit this question of surface areas entirely. This method was first thought to be of interest only in connection with the study of mortars; however, it was soon seen to be entirely general and applicable to coarse aggregates as well as to mixtures of fine and coarse aggregates. As a result of further studies of mortar and concrete mixtures we have developed a complete method of proportioning concrete on this basis. Our present method of computing the fineness modulus differs somewhat from that originally used, but the principle is the same.

This method means that so long as the sum of percentages from the sieve analysis is the same, we get essentially the same strength of mortar or concrete; in other words, the path of the sieve analysis curve has been shown in this way to be immaterial. We do not necessarily have to use a grading conforming to a predetermined sieve analysis curve in order to get the best results. By making many thousands of tests we have determined what the proper value of the fineness modulus is to give the concrete a maximum strength with different maximum sizes of aggregate and different quantities of cement. This having been determined, we have at once a direct method of proportioning the aggregate in a concrete mix. In this manner a sand of any grading can be combined with a coarse aggregate of any grading in a way to produce concrete of the best composition.

Needless to say, the amounts of water and cement in the mix have some influence on the value of fineness modulus which gives maximum strength, but those factors have been studied and we have pretty well worked out the relations involved.

A great deal may be said about water in concrete. We have studied the question of consistency very fully and have come to the conclusion that the water content is absolutely the governing factor. I do not mean to imply that concrete can be made without cement, but the strength and other properties

Mr. Abrams. of concrete are largely determined by the water-content of the mix. The grading of the aggregate reflects its influence upon the strength of the concrete only in so far as this factor dictates the amount of water which must be used in order to produce a plastic mix. An article by the speaker in the May 2d issue of *Engineering News-Record* brought out in a brief way the results of certain tests of this kind. In that article it is shown that, regardless of the mix or the grading of the aggregate, (so long as the aggregate is not too coarse for the amount of cement used) and regardless of the consistency (so long as the concrete is not too dry for a plastic mix), you get the same water-strength relation. In other words, we find a uniform variation in the water-strength relation, regardless of the reason for the change in water content, providing the amount of water in the mix is expressed as a ratio to the volume of cement. The water-ratio may be varied over a wide range due to variations in the proportions of cement, water and aggregate, or to differences in the grading of the aggregate. Regardless of the reason for varying the water content, the water ratio dictates once for all the strength of the concrete. Improvement in the grading of the aggregate and the use of more cement are simply devices which enable us to reduce the water ratio in the mix and still secure a workable concrete. This relation shows just how important the water factor is. For instance, we have found that in a one-bag batch of concrete the addition of one pint of water more than necessary produces the same effect as if we should leave out three pounds of cement. Engineers and builders who are using a great deal more water than necessary can easily compute the ultimate cost to somebody of the use of too much water in the mixture.

I have not had an opportunity to study Mr. Edwards' paper in detail, so I do not know exactly how his results compare with ours. We have during the past three years used our fineness modulus in making studies of the relative merits of different sands similar to those indicated by Mr. Goldbeck in the case of surface areas.

Mr. Bates. MR. P. H. BATES.—It may be of interest to mention that frequent reference to the question of "surface factor" will be found in the yearly transactions of the American Ceramic

Society, many of the products in that field having been compounded on much the same basis as that described in Mr. Edwards' paper. A discussion of the question of surface area appears in one of the early publications of that Society, I think about 1900, and reference is there made to the work along that line of an Englishman by the name of Jackson. **Mr. Bates.**

Mr. Davis. MR. WATSON DAVIS (*by letter*).—The admitted fact that mortar made from a coarse sand is stronger than that made from a fine sand is expressed in a new way by Mr. Edwards in his paper on proportioning of aggregates by the method of surface areas. His theory that the strength of mortar varies with the surface area of the aggregate, provided the ratio of cement to surface area is constant, is essentially the same as theories that have used the relation of cement to diameters of the particles (or which is the same thing, the percentage passing or retained on sieves) as an indication of strength. It should be noted that the area of a sphere varies as the square of the diameter. The difference between the surface area theory and the diameter theory would then be one of degree only, that is, the variation in strength between mortars made from fine and coarse sands should be greatest using the surface area theory.

Mr. Edwards has approached the subject from the opposite side to most investigators. Instead of assuming a proportion of cement to sand by weight, and studying the variation in strength, he has assumed a constant ratio of cement to surface area of sand and based his conclusions on the similar strengths obtained. Mr. Edwards, in expecting these equal strengths, has assumed as the basis of his theory that if the strength of mortar varies directly with the cement content it varies inversely with the surface area of the sand. In other words, of two mortars or concretes of the same consistency, mixed according to Mr. Edwards' tables and diagrams, the one with twice the surface area of aggregate per unit of cement should have just half the strength, regardless of the mix.

This assumption is not borne out by a series of tests that have been made on different sands of silicious origin in different mixes. From the accompanying Fig. 4 it may be seen that the strengths and surface areas are not related by any such fixed ratio, but that sands varying considerably in surface area

Mr. Davis. may give practically equal strengths. In a series of tests using sands of artificial gradation it has been shown even more clearly that the surface area theory does not hold.

There are no data in Mr. Edwards' paper that attempt to show that his method of proportioning will apply to concrete mixes, as the concrete tests were made ignoring the surface areas of the coarse aggregates. Such data are necessary to make the theory general, as any method of proportioning should apply to mortars and concretes equally well.

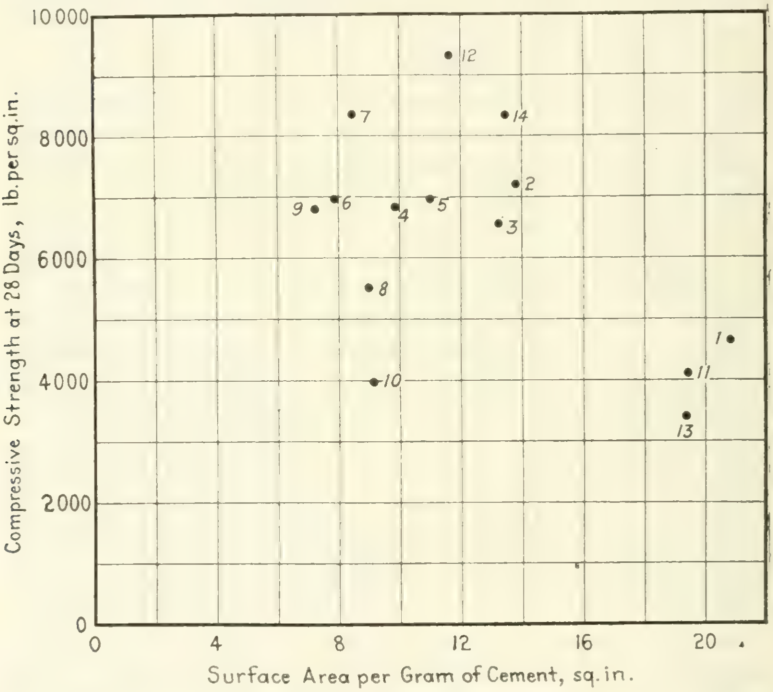


FIG. 4.—Diagram showing Compressive Strength in lbs. per sq. in. for Sands with Different Surface Areas per Gram of Cement.

A theory of proportioning that applies only to mortars and not to concretes would be relatively unimportant, as concrete is used far more widely than mortar.

Regarding the conclusion, numbered 9, which states that tests indicate a probable definite relation between the com-

Mr. Davis.

pressive strength of concrete and the compressive strength of the mortar of the concrete mix, tests at hand show that concretes of practically equal strength can be obtained using either fine or coarse sand, by making the ratio of coarse aggregate to fine sand greater than the ratio of coarse aggregate to coarse sand. In such a case, if test cylinders had been taken of the mortar of the mixes, as Mr. Edwards did in his tests, the fine-sand mortar would undoubtedly be weaker than the coarse-sand mortar. As the concrete was practically of the same strength, the relations between mortar and concrete strengths would be different in the two cases.

Mr. Edwards might have saved himself the work of counting thousands of sand grains by dividing the weight of a given volume of sand by the weight of an average particle, assuming particles spherical. Even had he assumed that the average diameter of the sand particles sizing between two sieves is the average of the diameter of the openings of the sieves, he probably would have obtained a result as accurate as by the assumption that the sand particles are all spherical. However, it is known that with fine cement particles, the average diameter of the particles passing a sieve is larger than the nominal opening of the sieve, and it is logical to assume that this relation holds with sands. The following is a quotation from page 50 of Technologic Paper 48 of the Bureau of Standards, by J. C. Pearson and W. H. Sligh, entitled "An Air Analyzer for Determining the Fineness of Cement":

"In ordinary mechanical analyses of sand no attention is paid to absolute sizes of grains, but the nominal sizes of the screen openings are taken as the sizes of separation. These nominal openings are always less than the absolute size of separation, partly because some screen openings, especially in the finer sieves, are always larger than the nominal opening, partly because the nominal size corresponds more nearly to the mean of the length, breadth and thickness. These two factors have the combined effect of making the nominal screen opening correspond very nearly to the average thickness; that is, the average smallest dimension of the particles representing the size of separation. The thickness of the 100 and 200-mesh particles were determined as 0.00553 and 0.00298 in., respectively;

Mr. Davis. the nominal 100 and 200-mesh openings being 0.0055 and 0.0029 in., respectively."

Using these facts as a basis, it would seem logical to assume the diameter of the particles as the diameter of opening of the larger of the separating sieves. It is interesting to note that the diameters that Mr. Edwards figured from his actual counts are nearly equal to diameter of opening of the larger of the separating sieves. Using standard Ottawa sand, assuming the particles spheres, and using as the average diameter, 0.034 in., the size of opening of the 20-mesh sieve, the number of sand particles in a gram would be 1160.[1] Mr. Edwards

TABLE I.

Mix No.	Percentage of Sand Retained on Sieve No.									Passing the 100 Sieve.	Surface Area of Sand per Gram of Cement, sq. in. (using Edwards' Diagram.)	Percentage of Water.		Compressive Strength at 28 Days, lb. per sq. in.
	4	8	10	20	30	40	50	80	100			By Edwards' Formula.	Used in Mix.	
1	0	0	0	1	10	20	35	22	9	2	20.8	11.0	15.5	4560
2	0	3	5	14	21	25	21	7	3	1	13.8	9.8	12.7	7050
3	0	4	3	22	31	23	13	4	0	0	13.2	9.7	11.7	6470
4	3	14	5	25	23	15	10	4	1	0	9.8	9.2	10.8	6700
5	0	50	0	1	5	10	18	10	5	1	11.0	9.4	11.0	6870
6	0	50	3	8	10	13	10	4	1	1	7.8	9.0	11.0	6830
7	0	50	0	6	8	17	12	5	2	0	8.4	9.0	11.3	8240
8	0	0	0	0	100	0	0	0	0	0	9.0	9.1	10.5	5470
9	0	66	0	4	5	11	8	3	2	0	7.3	8.9	11.5	6780
10	67	5	2	3	3	6	5	5	3	2	9.1	6.5	10.7	3810
11	0	2	3	10	13	17	13	16	11	5	19.4	10.7	13.3	4060
12	0	50	1	5	7	9	12	8	6	2	11.6	9.5	12.3	9200
13	0	0	0	2	12	27	34	19	6	0	19.3	10.7	13.9	3340
14	0	50	0	1	6	14	32	9	3	0	13.4	9.8	12.3	8230

All mixes were 1 : 2 by weight except No. 10 which was 1 : 3.
2 by 4-in. cylinders used as test pieces, stored in water.
Consistency throughout was slightly wetter than normal cement-testing consistency, but was uniform.

---

[1] The formula used was—

$$\text{Number of particles per gram} = \frac{1 \text{ gram (weight of sand)}}{\frac{4\pi}{3}\left(\frac{\text{diameter, in.}}{2}\right)^3 \times \text{(Specific gravity)} \times 16.38}$$

Mr. Davis. found the number to be 1323 by actual count. It is doubtful whether it is justifiable, either mathematically or practically, to carry the computations in Tables III and IV to five and six significant figures.

It is unfortunate that Mr. Edwards did not separate the sand particles that he counted by the series of commonly used sieves, in which the sieve openings increase by a fixed relation to powers of the square root of 2, as this series is more rational and convenient than the 10, 20, 30, etc., series.

The results given by Mr. Edwards' formula for the quantity of water to be used in his "normal" consistency mortars, seem to be low and mortars mixed accordingly would be very dry. It can be easily figured that in the cement testing mix of one part cement, by weight, to 3 parts of the standard Ottawa sand assuming a cement requiring 23 per cent of water for a normal consistency paste, the percentage of water in the mortar, by Mr. Edwards' formula, would be 7.3, while that required by the specifications is 10.3. This discrepancy holds not only for the uniformly graded Ottawa sand mixes, but also for the ordinary sand mortar mixes, as is shown by the accompanying Table I or by simple computations.

Acknowledgment.—The writer is pleased to make acknowledgment to Mr. J. C. Pearson of the Bureau of Standards for his aid in the preparation of this discussion.

Mr. Edwards. MR. L. N. EDWARDS (*Author's closure by letter*).—"Facts are stubborn things." Since we do not look at them from the same point of view we cannot see alike. It is this very difference of view which, in the long run, gives the real value to the exchange of ideas among us, by ultimately bringing things into their true perspective.

What are the conditions that should determine the practical value of any method of proportioning the materials of mortars and concretes? Having in mind that experience has repeatedly demonstrated that the best results are produced by the workman understanding the fundamental principles involved in his work and the use of the tool with which he must execute the details, the author believes that to be of greatest value any method for both laboratory and field use in its final working form should not be encumbered with mathematical operations restricting its

Mr. Edwards. interpretation to a comparative few, but instead should involve only the simplest mathematical processes and should be founded upon principles readily understood by engineers, architects, laboratory men, inspectors, superintendents of construction, foremen, and even by intelligent laborers. In short, its salient features should be simplicity of theory and the adaptability of a well-devised working tool. That the author's viewpoint differs from the viewpoints of some who have contributed to the discussion of his paper is clearly apparent.

Mr. Johnson entertains the opinion that the surface area method of proportioning is, as he expresses it, "unnecessarily cumbersome." He points out that surface areas of particles are direct functions of mean diameters and claims that these diameters may be expressed in terms of sieve openings. It would be interesting to know just how Mr. Johnson arrives at this conclusion. However, quite apart from this detail, it must be borne in mind that sieve openings are linear functions, while surface areas are functions of the squares of diameters. The many factors tending to render difficult the practical application of the mechanical analysis method of proportioning are very briefly referred to by Mr. Johnson. That the proper interpretation of these factors involves judgment matured by a considerable amount of experience is generally conceded. Broadly speaking, the mechanical analysis of the materials used as the basis of this method is embraced by the surface area method. The personal factors of the former are eliminated to a marked degree in the latter by the use of simple scientific and mathematical considerations.

Prior to the chemical union of the cement and water forming the cement matrix, there undoubtedly exists for a brief period of time points of contact between the cement and the sand particles which are distributed over the surface areas of the sand and are, therefore, to all intents and purposes, functions of these areas. Mr. Johnson's claim that surface area proportioning is in this case deceptive does not appear to be well founded.

In the assumption used as the basis for his "cement per grain" ratio, Mr. Johnson has apparently failed to take account of one quite important factor influencing the number of sand

Mr. Edwards.

grains in a given volume of mortar. Tests made with sand C, using a normal-consistency 1 : 3 mix, indicate a distending or "bulking up" effect amounting to somewhat over 15 per cent. The error in the computed number of particles, therefore, appears to amount to several billions. Except for calling attention to this very commonly disregarded factor in mortar and concrete making, this correction would be of no moment.

A critical examination of the discussion by Mr. Davis discloses the fact that he has labored under a misconception of the fundamental principle of the surface area method. There are some general considerations, however, in his discussion which it might be well to review carefully.

A comparison of the mathematical functions involved will show quite conclusively that even from a purely mathematical point of view the difference between the surface area method and other methods involving the diameters of particles is so complicated that it cannot be correctly described as "one of degree only."

In regard to Mr. Davis' suggested use of approximate methods for the purpose of saving labor, it seems pertinent to remark that from the beginning of the author's investigation it was recognized that certain unavoidable approximations must be made. Various other approximations, including those suggested by Mr. Davis, were taken under consideration and a careful study made of their possible effects upon final results. The course of procedure finally adopted was to eliminate all approximations possible without consideration for the time and labor thus involved. This course was justified by the fact that data relating to the probable limiting ranges of numbers of sand particles as well as the averages used as a basis for the tests were thus secured.

Practically all published data of mortar and concrete tests involving sieve analyses of sands are based upon the sieve series used in the author's tests. It is probable that more sieves of this series are now in use than of the series in which the openings vary by a fixed relation to powers of the square root of 2 although, the latter is unquestionably a more rational arrangement of sizes.

The author did not include in his paper a discussion of the

Mr. Edwards. general application of his consistency formula to sands of other rock origin than that used in his tests, for the reason that he believed it to be self-evident that the constant (210) in the formula is somewhat dependent upon this particular item of sand origin.

Mr. Davis does not make it clear just what rule he used in determining the water content recorded in his Table I. If he used the rule "guess by eye," it is safe to say that he did not secure uniform consistency mixes. In this connection, it will be noted that 50 per cent of the sands described in that table are "freak" sands. With respect to these sands, it seems reasonable to assume that any scientific method of proportioning applicable to normal sands would be somewhat inapplicable to them, since their use involves factors which materially affect the physical properties of mortars and concretes.

EFFECTS OF GRADING OF SANDS AND CONSISTENCY OF MIX UPON THE STRENGTH OF PLAIN AND REINFORCED CONCRETE.

By L. N. Edwards.

SUMMARY.

This paper is supplementary to the paper of the same title[1] presented at the last annual meeting of the Society. It contains, in addition to the results of the one-year age tests of sand grading and consistency of mix specimens, the results obtained in a consistency-abrasion test made with the object of determining the effect of consistency of mix upon the resistance of concrete to abrasion and shock.

The results of a series of gravel concrete tests are contained in an appendix to the paper. These tests were made from similar materials and under the same conditions as existed in the grading of sands and consistency of mix tests.

---

[1] *Proceedings*, Am. Soc. Test. Mats., Vol. XVII Part II, p. 301 (1917).

EFFECTS OF GRADING OF SANDS AND CONSISTENCY OF MIX UPON THE STRENGTH OF PLAIN AND REINFORCED CONCRETE.

By L. N. Edwards.

This paper is primarily intended as a supplement to the author's paper presented under the same title at the last annual meeting of the Society.[1] The curves showing the compressive strengths of the test cylinders for both the "Tests for Grading of Sands" and the "Tests for Consistency of Mix" have been revised to include the strength of cylinders tested at the age of one year. The information relating to the effect of consistency of mix is augmented by the addition of the results of a test made to show the decrease of the resistance to abrasion and shock resulting from the inclusion of a water content in the mix in excess of that required "to produce a concrete, the mortar component of which is of a saturated, sticky, semi-plastic consistency."

In 1917 a series of tests was made by the City of Toronto, Department of Works, to secure information relating to the strengths to be obtained from concretes in which gravel was used as aggregate. The description of materials, methods, etc., together with the results secured from these tests, are fully described in an appendix to this paper. The sand and gravel used came from the same pit as did the sand used in the 1916 broken stone concrete tests.

All tests were made under the direct supervision of the author.

Results of Tests.

In plotting the curves showing the compressive strengths of test specimens for ages of 90 days and under, the strengths obtained from the 90-day tests were in all cases assumed to be unchangeable and in a few cases slight variations from plotted strengths at 7, 30 and 60 day ages were made to secure uniform,

---

[1] *Proceedings*, Am. Soc. Test. Mats., Vol. XVII, Part II, p. 301 (1917).

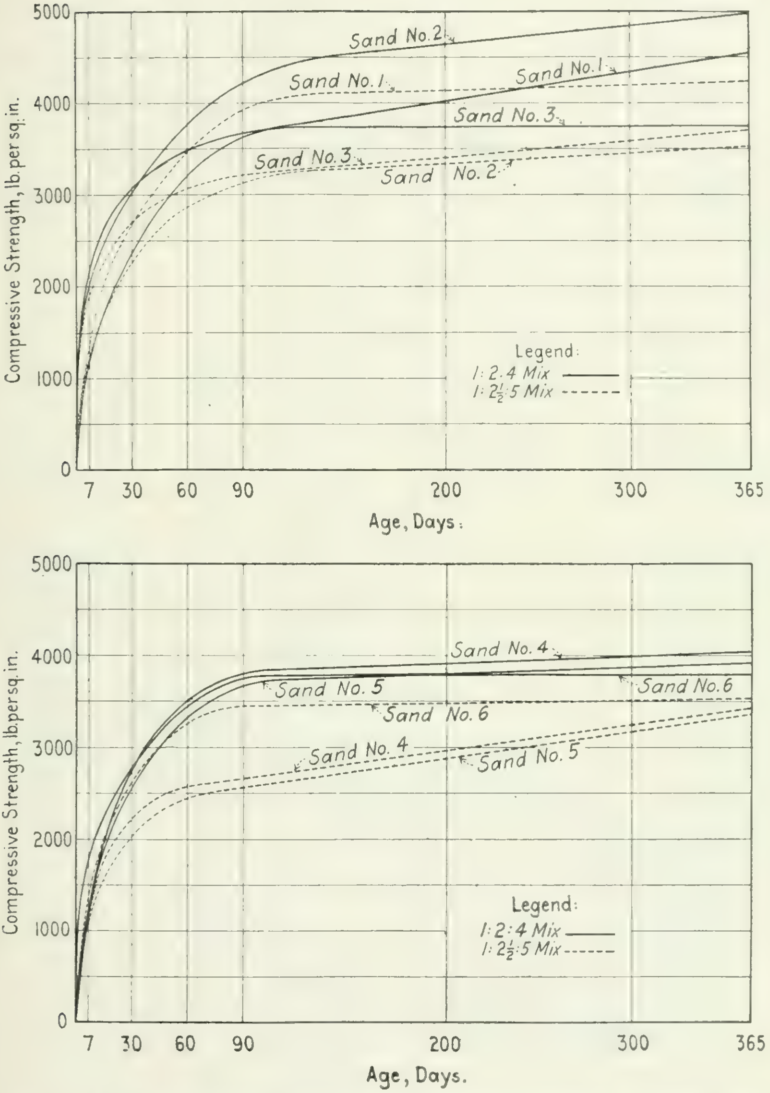


FIG. 1.—Compressive Strengths of Test Cylinders: Grading of Sands Test.

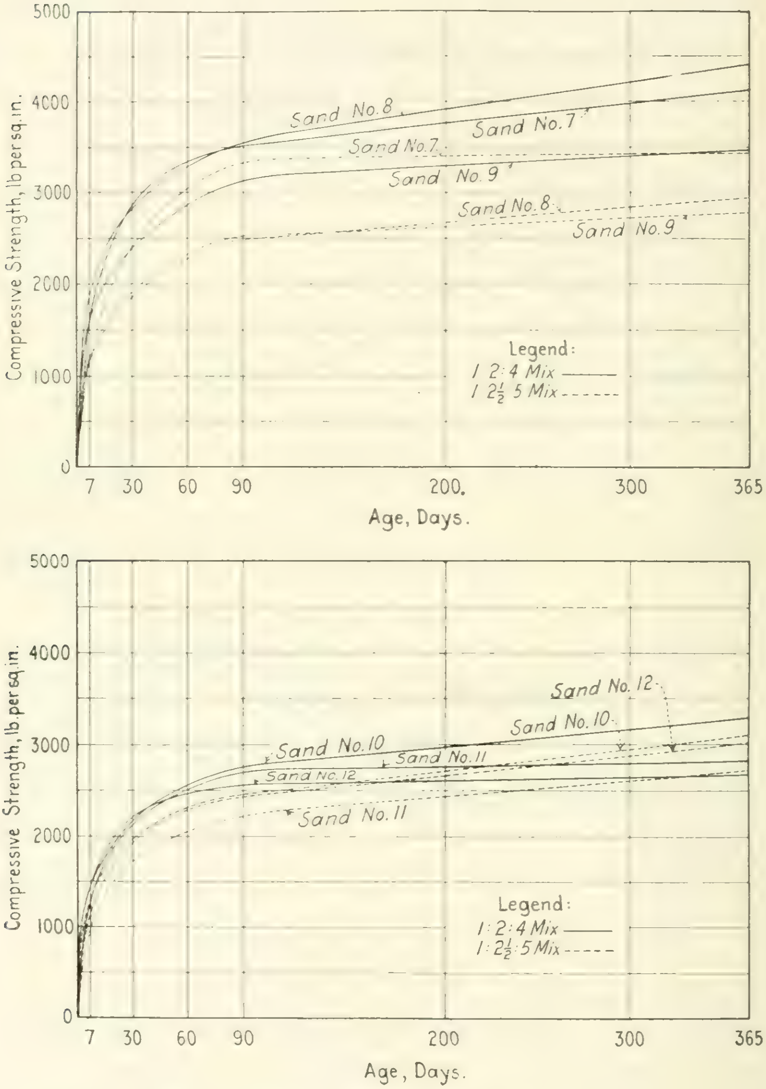


FIG. 1.—Grading of Sands Test (*Continued*).

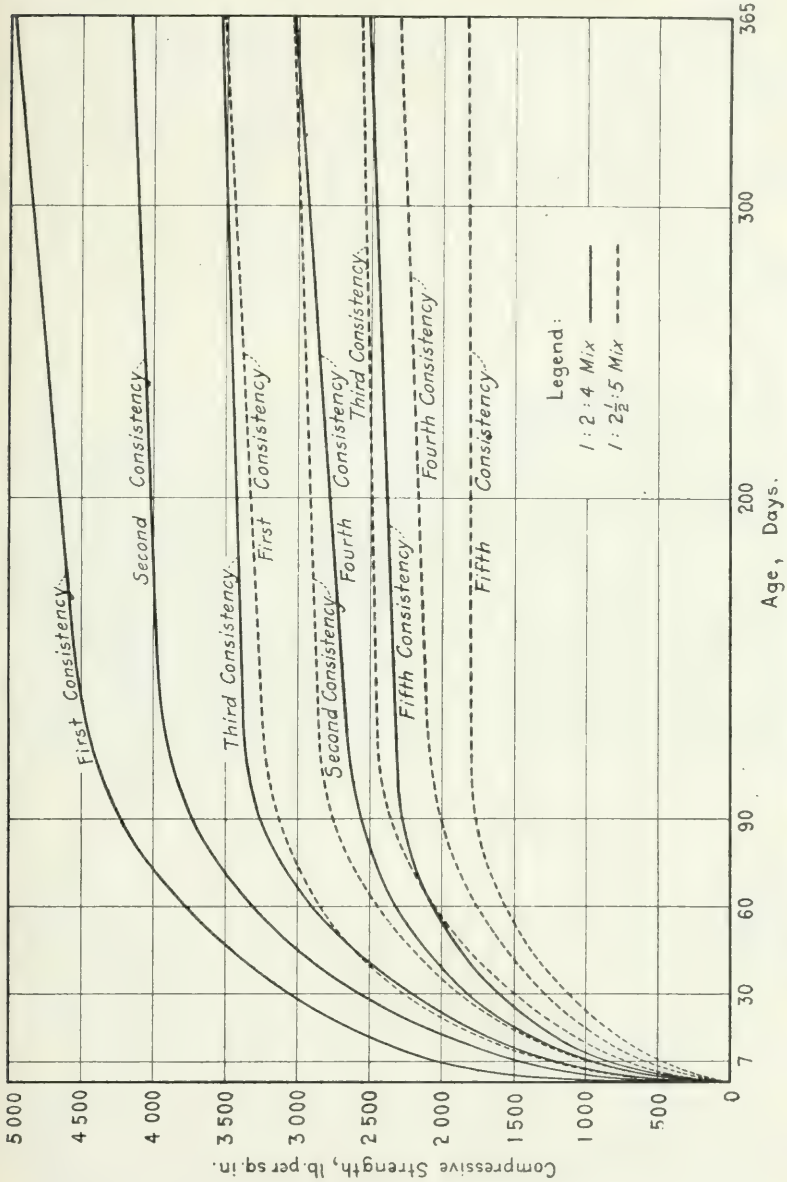
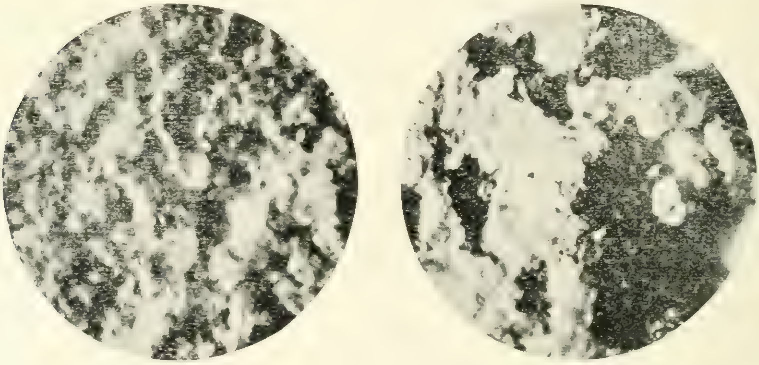


FIG. 2.—Compressive Strengths of Test Cylinders: Consistency of Mix Tests.

even curves. In revising these strength curves to include the 1-year test strengths it has been found advisable, in a few cases and for the same reason, to vary from the plotted strengths at 90 days.

Tests for Grading of Sands.—Fig. 1 shows the compressive strengths obtained from the tests of the cylinders in which the twelve specially graded sands were used.

Tests for Consistency of Mix.—Fig. 2 shows the compressive strengths obtained from the tests of the cylinders in which the consistency of mix was varied from a sticky, semi-plastic to a very wet condition. In relation to the total weight of the cement and aggregates the quantity of water used in the first consistency mix was 6.17 per cent for the 1:2:4 mix and 5.99 per cent for the $1:2\frac{1}{2}:5$ mix. This quantity was increased by 10, 20, 35 and 50 per cent, respectively, for each succeeding mix.



(*a*) First Consistency. (*b*) Fifth Consistency.

FIG. 3.—Photomicrographs of Mortar Bedding of Stone Aggregate—Consistency of Mix Tests. (×75.)

In the previous paper mention was made of the condition that "the inclusion of a greater quantity of water than is required for the development of its natural functions is decidedly detrimental to the strength and reliability of the final concrete," and photographs were reproduced showing accumulations of water cavities underlying the particles of stone aggregate and the reinforcing steel tending to reduce the bearing capacity in the former case and the bond between the steel and the concrete in the latter case.

A microscopic examination of the mortar portions of the concretes of the five different consistencies discloses a marked change in the physical structure of the cement matrix. Doubtless the decrease in strength found in the tests of concrete cylinders and of reinforced concrete beams is in part due to this change in the matrix.

Fig. 3 shows photomicrographs (×75) of the mortar bedding of stones in first and fifth consistency concretes. Under the microscope the cement matrix of the first consistency concrete appears gray in color and adheres closely to the surfaces of the aggregates in amorphous masses containing myriads of minute voids, but on the whole giving the impression of possessing strength, hardness and rigidity. In comparison, the cement matrix of fifth consistency concrete presents a marked difference, both in color and in physical structure. Its color is more nearly a milky white and its structure is generally loose and flaky, giving ample evidence of a lack of strength resulting from absence of cohesion between the cement particles and adhesion between these particles and the surfaces of the aggregates.

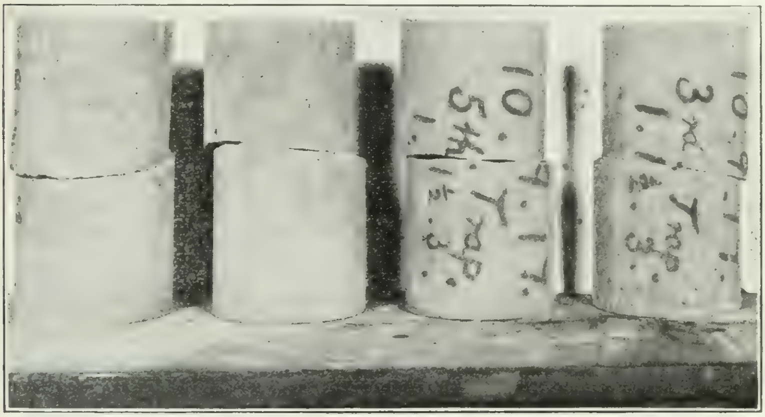


FIG. 4.—Test Specimens: Consistency-Abrasion Test.

Consistency-Abrasion Tests.—This test was made with the object of obtaining information relating to the influence of the consistency of mix upon concrete in relation to its resistance to abrasion and shock. The mix used was a 1:1½:3. Two sets of test cylinders were made. In the first set the stone aggregate was broken limestone of good quality and in the second set a good quality of broken trap rock was used. In the first consistency mix the water content was 6.25 per cent of the total weight of the cement and aggregates. The water content was increased by 10, 20, 35 and 50 per cent for the four succeeding consistencies. The test specimens were cast in 6-in. cylinder forms by the insertion of a metal diaphragm at about the center of the length. Fig. 4 shows the specimens so produced. Ten half cylinders were made for each consistency.

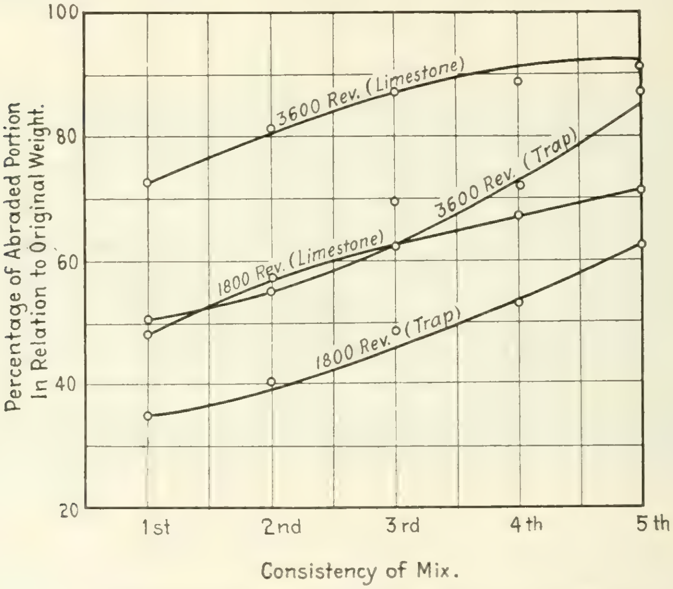


FIG. 5.—Relative Reductions of Test Specimens: Consistency-Abrasion Test.

The specimens were tested at the age of three months by the "rattler" abrasion test commonly used for testing paving brick. Fig. 5 shows the percentages of reduction in weight resulting from 1800 revolutions and from 3600 revolutions of the machine. In this test several of the "wet" consistency specimens were entirely pulverized.

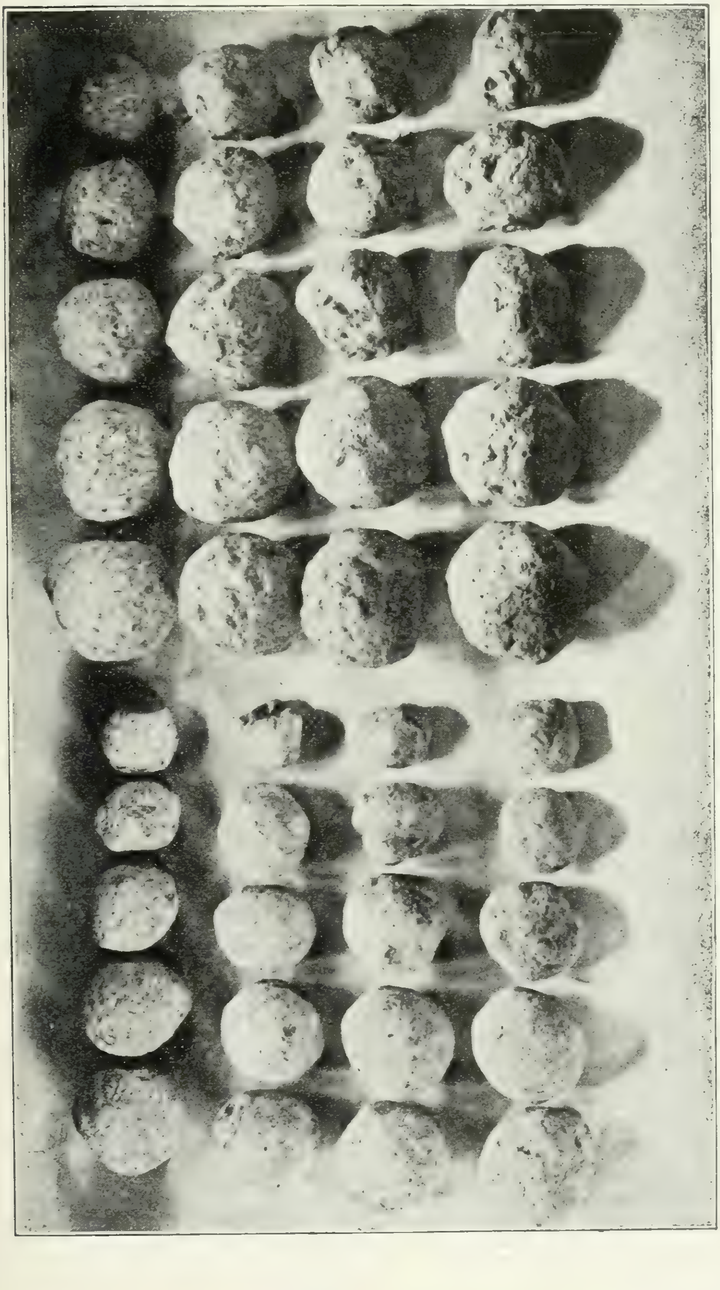


FIG. 6.—"Rattled" Test Specimens: Consistency-Abrasion Tests. Limestone Aggregate Specimens at Left, Trap Aggregate Specimens at Right. Consistencies arranged in Order from Left to Right.

Fig. 6 shows typical specimens for each consistency after final removal from the testing machine. The trap concrete specimens are shown at the right; the limestone concrete specimens at the left. Consistencies are arranged in order from left to right.

CONCLUSIONS.

The one-year tests have produced no information from which the author finds reason for modifying the conclusions contained in his 1917 paper. However, this further conclusion seems pertinent:

The increment of strength developed between the age of 90 days and 1 year is not constant and cannot be predetermined. In so far as "wet" concretes are concerned this increment is almost negligible.

The results obtained in the consistency-abrasion test indicate that the excess water in an over-saturated concrete reduces its resistance to abrasion and shock.

APPENDIX.

STRENGTH TESTS OF GRAVEL CONCRETE.

In the concrete tests herein described the aggregates were secured from the Maple Sand and Gravel Co., Maple, Ont. The sand used in 1916 in connection with the "Grading of Sands" and "Consistency of Mix" tests described in the author's paper last year was secured from the same company.

Throughout this series of tests the sizes of test specimens and the methods of proportioning, mixing, placing, storing, testing, etc., were the same as those used in the above-mentioned tests. In all cases only a sufficient quantity of water was used to produce a saturated, semi-plastic mortar adhering freely to the gravel particles. These tests are, therefore, directly comparable with the tests previously made in so far as similar aggregates of limestone origin were used in both cases.

TABLE I.—SAND AND GRAVEL GRADINGS.

Sand Grading.		Gravel Grading.	
Sieve No.	Percentage Retained on Sieve.	Screen Size, in.	Percentage Retained on Screen.
4	0.0	2	0.0
8	14.0	1½	15.0
10	4.0	1	26.0
20	14.0	¾	20.5
30	9.0	½	14.0
40	11.0	¼	24.5
50	14.0		
80	20.0		
100	6.0		
200	6.0 2.0 (passing)		

MATERIALS USED IN TESTS.

Cement.—As compared with the cement used in the 1916 tests, the "Canada" brand cement used in these tests developed in the 7 and 28-day tests a strength 10.8 per cent less than that used in 1916, the same standard tests being used.

One cubic foot of cement was assumed to weigh 100 lb.

Sand and Gravel.—The pit run gravel secured for the tests contained by weight 65.2 per cent of sand passing a No. 4 sieve and 34.8 per cent of gravel. The gradings of these portions are shown in Table I.

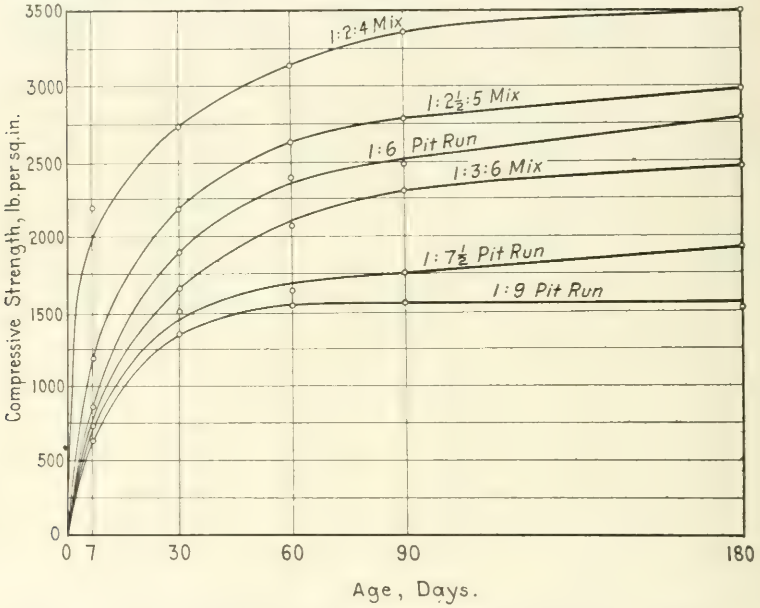


FIG. 7.—Compressive Strengths of Gravel Concretes of Different Mixes.

In its original state this material contained 7.59 per cent of moisture, of which the sand portion contained 5.86 per cent. This moisture was not dried out but was taken into account in proportioning the sand and the water contents of the mix.

The unit weights assumed for proportioning the mix were as follows:

One cubic foot of sand assumed at 100 lb.
One cubic foot of pit run gravel assumed at 110 lb.
One cubic foot of screened gravel assumed at 110 lb.

The screened gravel and the sand used in the regularly proportioned mixes were obtained by passing the pit run material over a screen having four meshes per linear inch.

RESULTS OF TESTS.

The tests of a 1:3 "normal" mortar, in which the aggregate was the sand used in these tests, showed at 28 days' age a tensile strength of 412 lb. and a compressive strength of 3312 lb. per sq. in. Briquettes and 2-in. cubes were used for these tests.

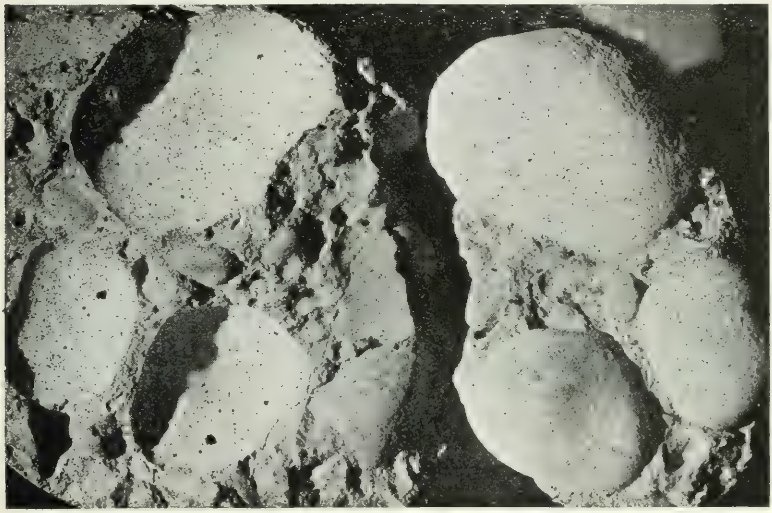
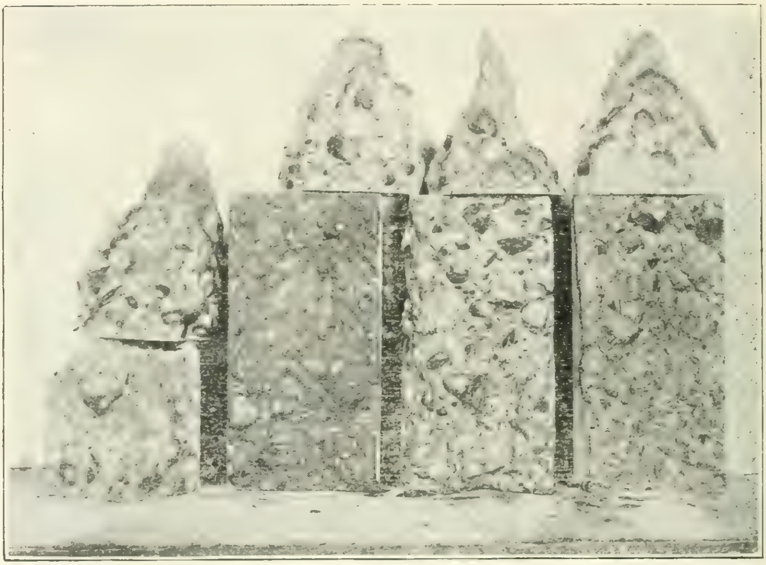


FIG. 8.—Surface Contact between Under Side of Gravel Particles and Mortar Bed, 1:2:4 Mix.

Fig. 7 shows the compressive strengths obtained from the tests of the 6-in. cylinders prepared from each mix. Five specimens were tested at each age of 7, 30, 60, 90 and 180 days.

Fig. 8 shows the mortar bedding of gravel particles in a 1:2:4 mix. The gravel particles removed from the beddings are shown at the right side of the photograph. This photograph is typical of the beddings found in specimens of all mixes. However, the porosity and the color of the mortar portion varied with the quantity of cement in the mix.

Fig. 9 shows broken cylinders of various mixes. It will be noted that the portions of gravel concrete cylinders contain very few broken particles, while the cylinder at the extreme right containing broken stone aggregate shows a considerable number of fractured particles. This failure of the mortar portion of the concrete, leaving the gravel particles intact, was typical of all mixes. The excess of mortar in the pit run specimens is clearly shown in the photograph.



(*d*) (*c*) (*b*) (*a*)

FIG. 9.—Broken Concrete Test Cylinder of Various Mixes:

(*a*) Contains Broken Stone (Limestone) Aggregate, 1:2:4 Mix.
(*b*) Gravel Concrete, 1:2:4 Mix.
(*c*) Gravel Concrete, Pit Run, 1:6 Mix.
(*d*, upper) Gravel Concrete, 1 : $2\frac{1}{2}$: 5 Mix.
(*d*, lower) Gravel Concrete, Pit Run, 1:9 Mix.

EFFECT OF AGE ON THE STRENGTH OF CONCRETE.

By Duff A. Abrams.

SUMMARY.

It is frequently desirable to estimate the probable strength of Portland-cement concrete at ages other than those covered by the usual test periods. Erroneous conclusions have been drawn by many engineers and writers in discussing the age-strength relation for concrete on the basis of tension tests of cement and mortar briquettes. The data given in the paper are drawn from numerous published reports and from tests made under the writer's direction at Lewis Institute, Chicago.

There has been little change in the standard tension test for cement since the briquette test was first used by John Grant in London in 1859. The typical age-strength relation for briquette tests, which shows a retrogression in strength after ages of 1 to 6 months, does not represent the condition found in compression tests of mortar and concrete, since compressive strength increases indefinitely so long as the concrete does not dry out. It has been shown by Johnson and by Coker that the briquette is subjected to eccentric loading. It is the writer's belief that the age-strength relation for briquettes reflects the peculiarities of the test piece and not the characteristics of the material.

The age-strength relation for compression tests of mortar and concrete may be expressed by the following equation:

$$S = n \log a + k$$

where S is the compressive strength of the concrete, a is the age, and n and k are constants whose values depend on the quality of the cement and on other conditions of the test. Strength of concrete is a function of the logarithm of the age. The results of tests from many American and European laboratories show this law to apply for ages from 7 days to 9 years.

The objectionable features of the briquette call attention to the desirability of substituting a compression test for the present standard strength test of cement.

EFFECT OF AGE ON THE STRENGTH OF CONCRETE.

By Duff A. Abrams.

Introduction.

It is frequently desirable to estimate the probable strength of concrete at ages beyond those covered by the ordinary test periods. It is believed it will be of interest to inquire into the laws governing the change in strength of concrete and determine the factors which affect such relations.

Such a study seems specially necessary since there has been a marked tendency on the part of engineers and writers to draw erroneous conclusions with reference to the age-strength relation for concrete from a study of tension tests of cement and mortar briquettes.

In the following discussion the test data are drawn from numerous published reports and from tests made in the course of experimental studies carried out through the cooperation of Lewis Institute and the Portland Cement Association at the Structural Materials Research Laboratory, located at Lewis Institute, Chicago.

In the preparation of the material for this paper we studied the results from probably one hundred different series of tests from both American and European sources. We were overwhelmed with the mass of information available on the effect of age on the strength of mortar and concrete. There seems to be no limit to the number of tests one can uncover by a little search; in fact, nearly every book on concrete contains information of this kind. It was much more difficult to decide what to eliminate than what to use. In many instances the information concerning the tests was not quite so specific as in the examples given.

Strength Tests of Cement and Concrete.

The earliest tests of cement were made by applying a pulling stress to neat cement briquettes of a form resembling in all essentials our present standard specimen for strength tests of cement. The testing of cement by means of tensile stresses applied to a briquette seems to have been largely accidental and not the result of any rational analysis of the requirements for such a test. This specimen was first used in 1859 by John Grant, an English engineer, in testing cement for the Metropolitan Board of Works, London. Grant's tests were made on briquettes having a minimum section of $2\frac{1}{4}$ sq. in.[1]

Certain modifications have been made in the size and contour of the briquette and a few refinements in the methods of making the test, but the essential features of the present standard cement test are the same as used by Grant.

Concrete tests have generally been made in compression on cubes varying in size from 4 to 12 in. Recently cylindrical specimens 6 in. in diameter and 12 in. in length, or 8 by 16 in., have been used by a number of testing laboratories.

TENSION TESTS OF CEMENT.

Since briquettes have long been used as a method of testing cement, it will be of interest to note the relation between age and strength of cement as shown by tension tests on this form of specimen. Fig. 1 shows the average results of neat cement tests made on a large number of cements at ages up to 5 years, by the Municipal Testing Laboratory of Philadelphia. The strength increases rapidly with age up to 7 days; from 7 days to 28 days the rate of increase is much lower. From 28 days to 3 or 4 months there is a slight retrogression in strength. This curve has been widely quoted as showing the relation between the strength and age of neat cement. It will be shown that entirely erroneous conclusions have been drawn from attempts to deduce the age-strength relation for concrete from tests of this kind.

Fig. 2 shows the age-strength relation for tension tests of neat cement and 1:3 standard sand mortars made by the U. S. Geological Survey. These curves are probably typical of the results of recent tension tests of cements. Retrogression in strength occurs after ages of 3 to 6 months, and no recovery occurs during the period of the tests, that is, up to one year. Tests made by other testing laboratories show retrogression to begin at 28 days or earlier. In general the tensile strength of the briquette is little, if any, higher at one year than at 7 days.

---

[1] See *Proceedings*, Inst. Civ. Engrs., London, 1865–66 and 1870–71. These papers were published in book form in 1875 as "Experiments on the Strength of Cement," by John Grant.

Figs. 3 and 4 are from tests made by H. J. Force and R. Feret, respectively. These figures have been drawn with a logarithmic scale of ages. Almost any desired number of different series of age-strength tests of cement and mortar in tension may be found in the literature.

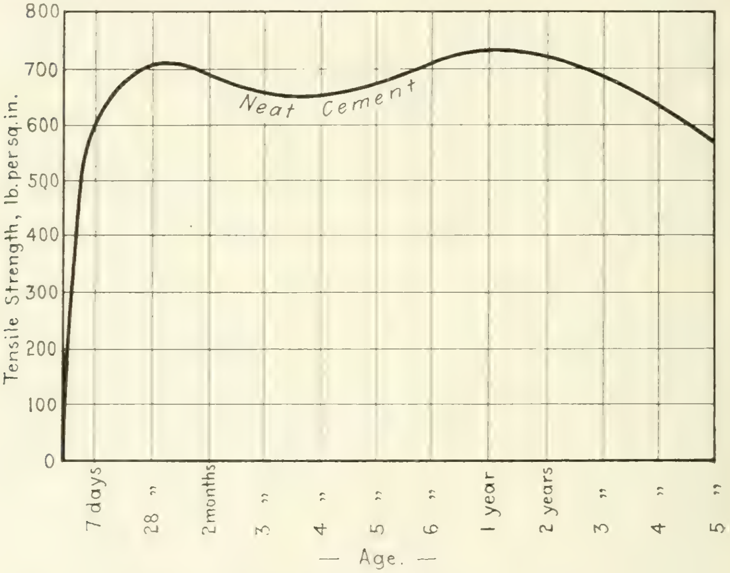


FIG. 1.—Tension Tests of Neat Cement. (W. P. Taylor, "Practical Cement Testing," 1906.)

These tests may be taken as representative of the relation found in hundreds of different instances in tests made by the writer, using many brands of cement, different mixes, etc. It may be stated that there is no uniformity in the age-strength relation, except that in a majority of instances a decided retrogression occurs at some period, generally between 28 days and 6 months. The richer mixes show earlier retrogression than the

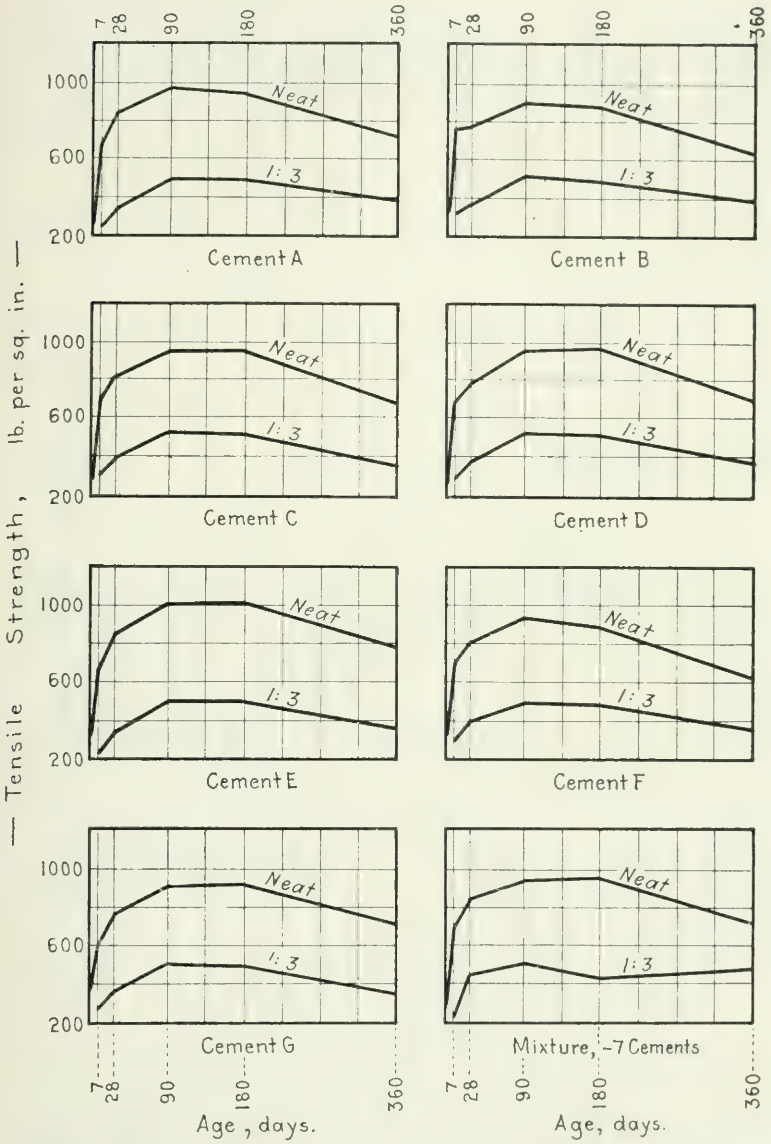


FIG. 2.—Tension Tests of Neat Cement and Sand Mortars (*Bulletin No. 331*, U. S. Geological Survey.)

lean ones. It will be seen below that this result is probably due to the form of the test specimen and the method of loading and does not reflect a characteristic of cement.

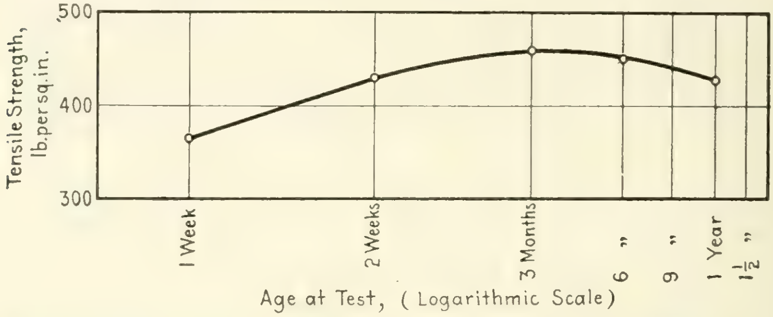


FIG. 3.—Tension Tests of Sand Mortar. (H. J. Force, *Proceedings*, Am. Soc. Test. Mats., Vol. XIV, Part II, 1914.)

COMPRESSION TESTS OF CONCRETE.

Since concrete is generally used to resist compressive stresses, it is natural that compression tests early found favor in studying the properties of concrete and in determining the strength of concrete on the work. Tests which have been reported show that the compressive strength of concrete tested

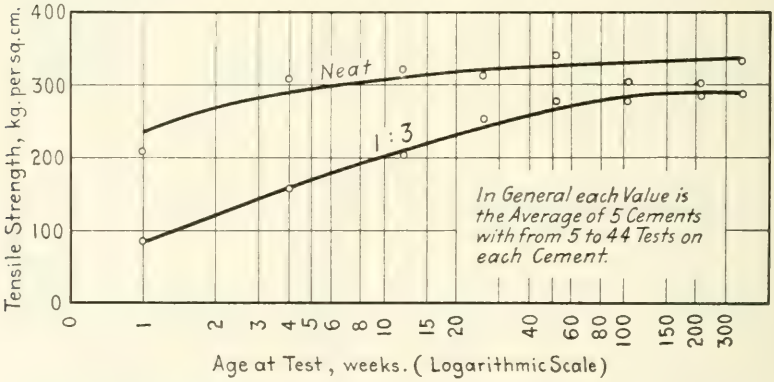


FIG. 4.—Tension Tests of Cement and Mortar. (Feret, "Chemie Appliquee a l'Art de l'Ingenieur," 1897, p. 346.)

in the form of cylinders having a length of two diameters is about 80 per cent of that of cubes.

Figs. 5 and 6 give the results of compression tests of 6 by 12-in. cylinders of different mixes tested at ages from 7 days to 3 months. Machine-mixed concrete was used; each value is the average of four tests from six different batches (total of 24 tests) mixed for periods of 15 seconds to 10 minutes. A 1:5 mix indicates 1 volume of cement to 5 volumes of graded aggregate up to $1\frac{1}{4}$ in. All specimens were stored in damp sand.

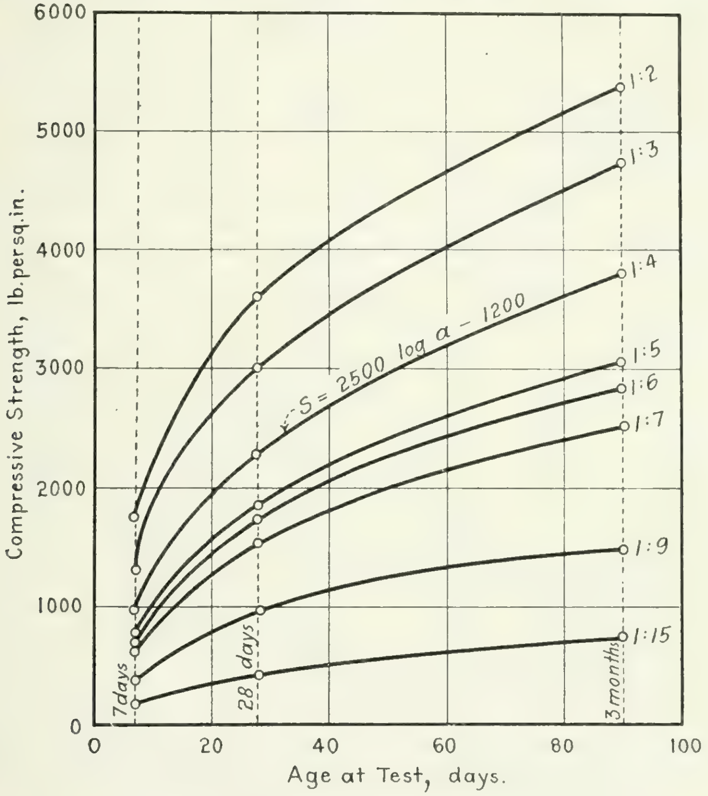


FIG. 5.—Compression Tests of Concrete; Age plotted to Natural Scale. (Lewis Institute Tests, Series No. 93.)

In Fig. 5, ages are plotted to a direct scale; in Fig. 6 the same data are plotted to a logarithmic scale of ages. The path of the lines may be expressed by an equation of the form,

$$S = n \log_B a + k \tag{1}$$

in which S = compressive strength of the concrete, a = age of test, B = base of logarithms used, and n and k are constants whose values depend on the quality of the cement and other conditions of the test; k may be positive or negative. If we use common logarithms (base 10), Eq. 1 becomes,

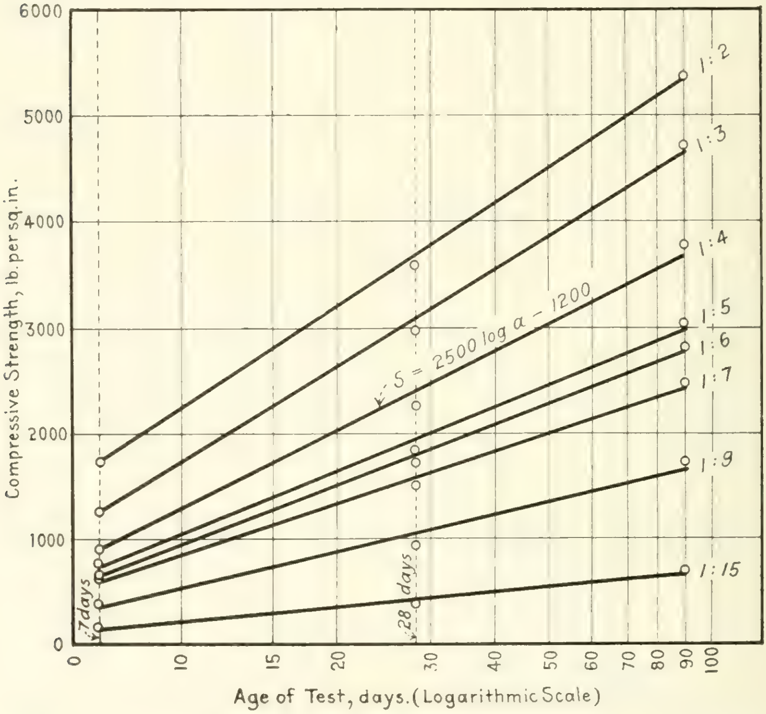


FIG. 6.—Compression Tests of Concrete; Age plotted to Logarithmic Scale. (Lewis Institute Tests, 6 by 12-in. Cylinders, Series No. 93.)

$$S = n \log a + k \tag{2}$$

This equation shows that for these tests the strength is a function of the logarithm of the age.

The constants may be found from Fig. 6. For the 1 : 4 mix, Eq. 1 becomes

$$S = 2500 \log a - 1200 \tag{3}$$

in which strength is expressed in pounds per square inch and age in days.

Figs. 7 to 16 gives the results of several other series of compression tests of concrete at ages varying from one week or one month to 6 or 9 years. These series were selected from a mass of data as typical of tests on concrete from cements of widely different characteristics made in both the United States and Europe. The diagrams include compression tests made on cubes and cylinders of both mortar and concrete, and crushing

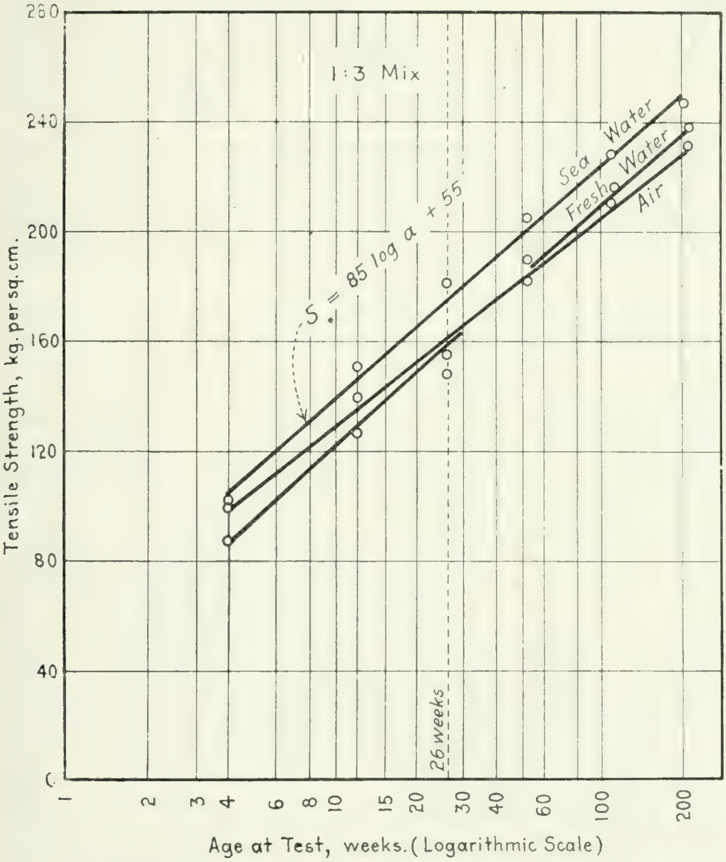


FIG. 7.—Tension Tests of Sand Mortars. (Feret, "Chemie Appliquee a l'Art de l'Ingenieur," 1897, p. 348.)

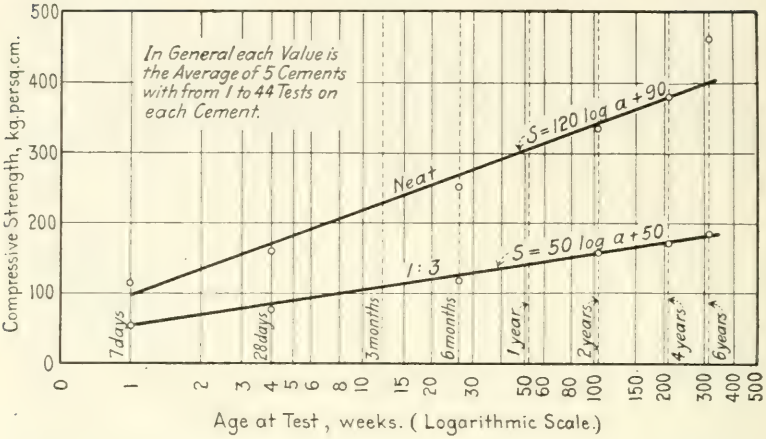


FIG. 8.—Compression Tests of Cement and Mortars. (Feret, "Chemie Appliquee a l'Art de l'Ingenieur," 1897, p. 348.)

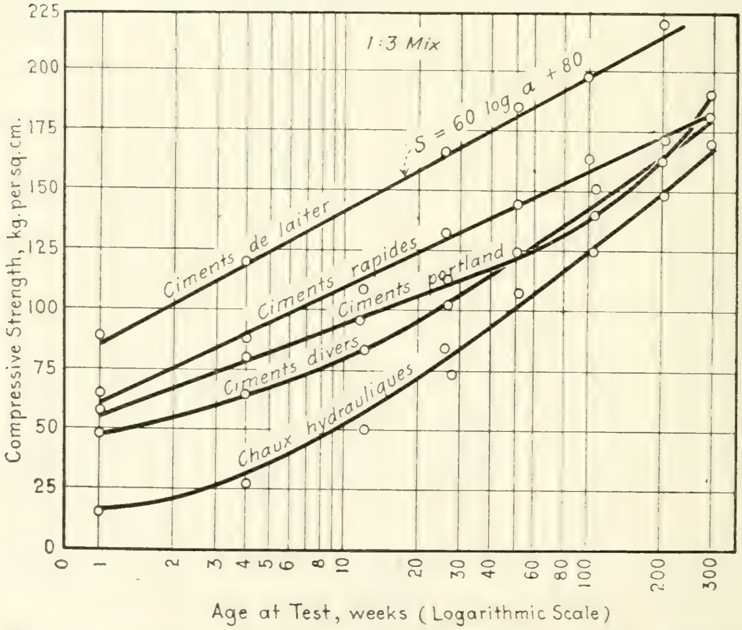


FIG. 9.—Compression Tests of Sand Mortars. (Feret, "Chemie Appliquee a l'Art de l'Ingenieur," 1897, p. 347.)

tests of concrete (Fig. 10). The strength of the concrete continues to increase with age, up to the longest period covered by the tests (9 years). This is true so long as the concrete does not dry out. The age-strength relation can be expressed by an equation of the form given by Eqs. 1 and 2. If the concrete dries out there is no further increase in strength (see Fig. 13). In general the age-strength relation may be expressed as a logarithmic function of the age of the concrete.

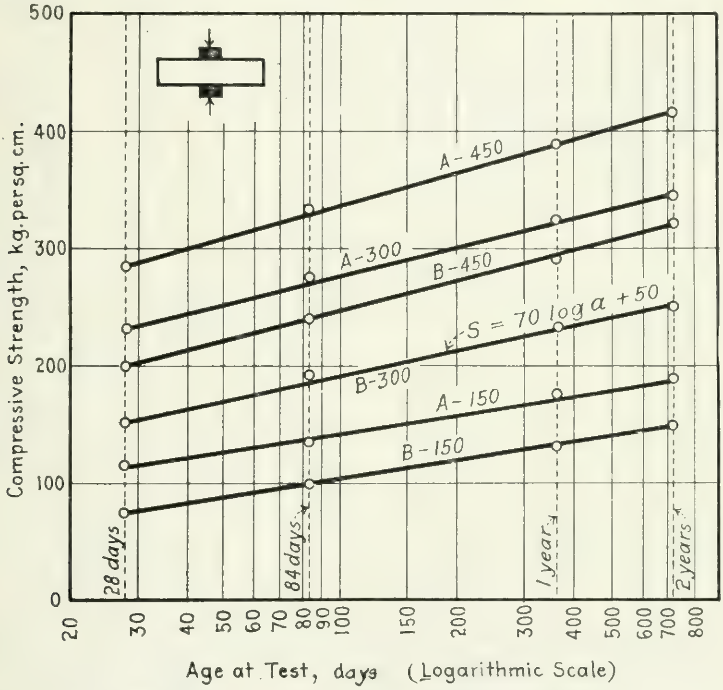


FIG. 10.—Crushing Tests of Concrete. (Schule, *Proceedings*, Inter. Assoc. Test. Mats., 1912, paper XII_1.)

It will be of interest to consider some of the results brought out by the logarithmic relation between age and strength shown in Eq. 2. The change in strength between any two ages is the same as the change between any other two ages which have the same ratio to each other as the first. For example the change in strength between 10 and 100 days is the same as between 100 and 1000 days. The increase in strength between

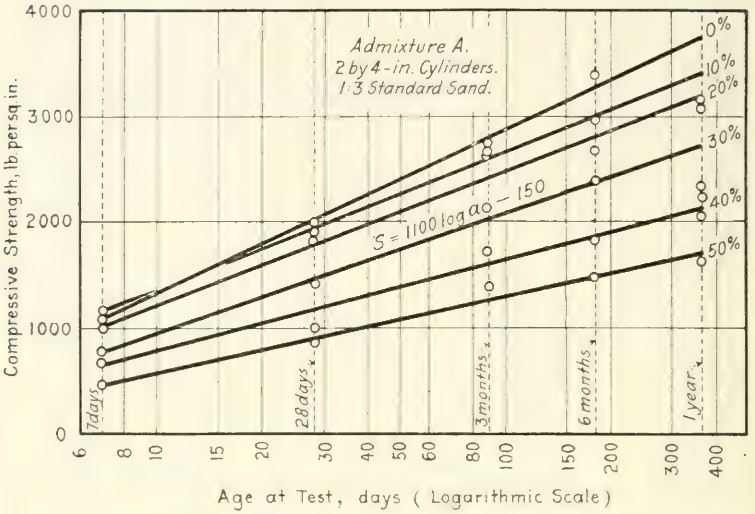


FIG. 11.—Compression Tests of Standard Sand Mortar. (Lewis Institute Tests, 2 by 4-in. Cylinders, Series No. 58.)

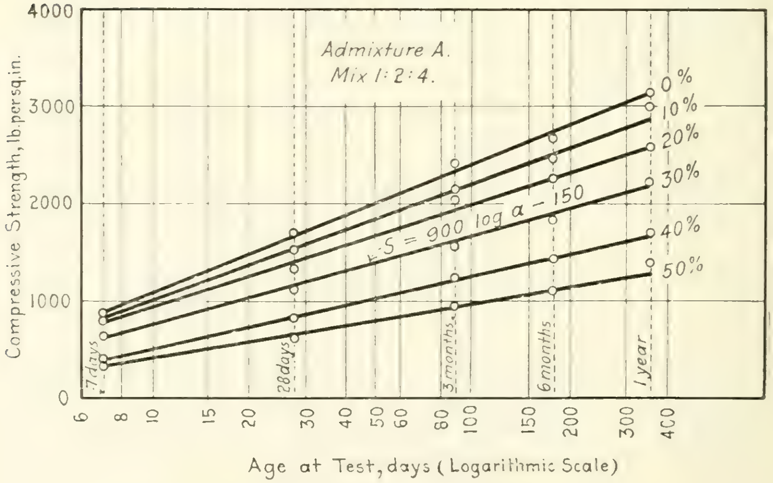


FIG. 12.—Compression Tests of Concrete. (Same Cements as in Fig. 11, 6 by 12-in. Cylinders.)

7 and 28 days is the same as the increase between one month and 4 months. This may be expressed mathematically by

$$S_2 - S_1 = S_4 - S_3 = S_6 - S_5, \text{ etc.,}$$

so long as $\frac{a_2}{a_1} = \frac{a_4}{a_3} = \frac{a_6}{a_5} = c$ which is a constant, where a_1, a_2, etc., refer to ages corresponding to strengths S_1, S_2, etc. For the examples just given, $c = 10$ and 4 respectively. If c is the base of logarithms used (same as B in Eq. 1), $S_2 - S_1 = n$, in Eqs. 1 and 2.

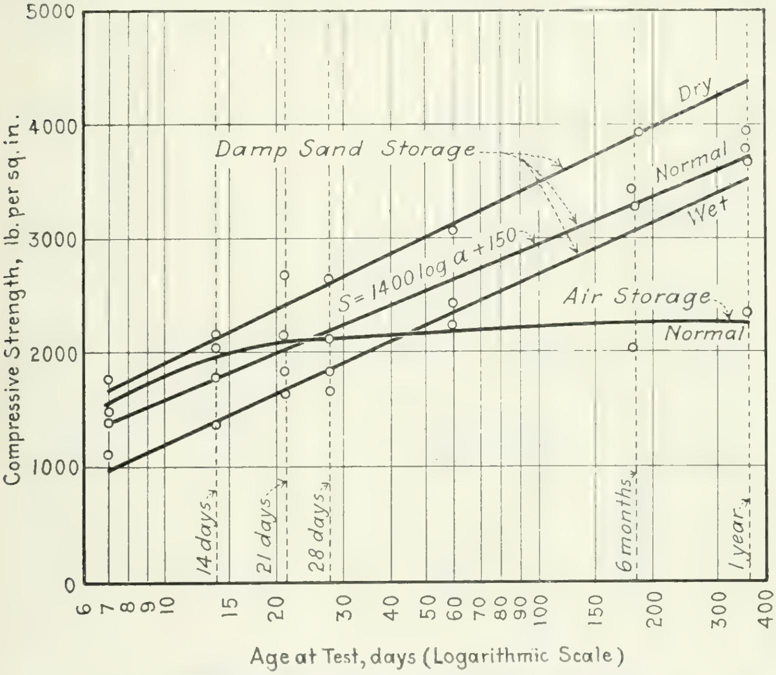


FIG. 13.—Compression Tests of Concrete. (University of Illinois Tests, *Journal,* Am. Concrete Inst., Oct.-Nov., 1914; 6 by 6-in. Cylinders, 1 : 2 : 4 Mix.)

It will also be seen that the value of n in Eqs. 1 and 2 is constant regardless of the units in which the age is expressed. In other words, the change in strength from d weeks to e weeks is the same as that from d months to e months, etc.

It should be noted that the equations given above do not give the proper relation if applied to ages below say 7 days.

Unwin[1] gives the following equation for the strength of cement and concrete at different ages:

$$y = a + bx^n \quad \text{.......} \quad (4)$$

For tension tests of cement and mortar he gives

$$y = a + b\sqrt[3]{x-1} \quad \text{.......} \quad (5)$$

and for compression tests of concrete

$$y = a + b\sqrt{x-1} \quad \text{.......} \quad (6)$$

in which y = strength, x = age in weeks, n = an exponent, and

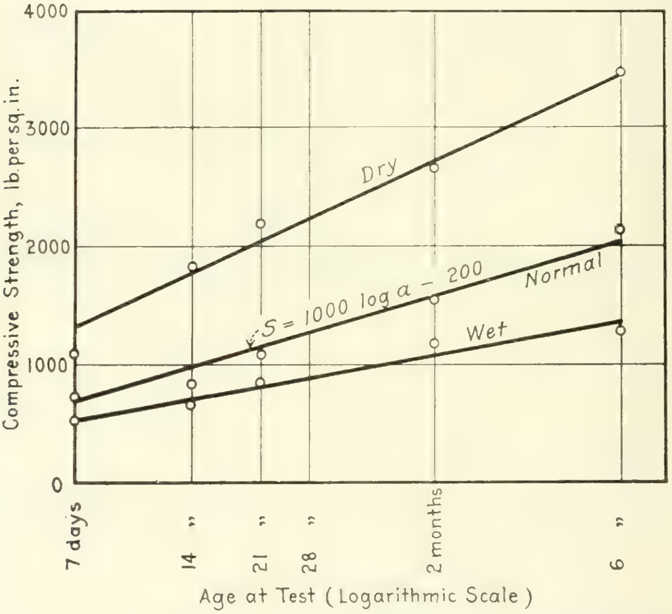


FIG. 14.—Compression Tests of Concrete. (University of California Tests, *Journal*, Am. Concrete Inst., Oct.-Nov., 1914; 6 by 6-in. Cylinders, 1 : 2 : 4 Mix.)

a and b are constants depending on the quality of the cement and the conditions of the test.

Unwin states that by means of this equation it is necessary to determine only one constant, since the value of a is the strength at 7 days. This, however, does not seem to be the case, since it is necessary to make some assumption as to the values of

---

[1] "The Testing of Materials of Construction."

n and to determine b. The value n has been assumed as $\frac{1}{2}$ for compression tests of concrete and $\frac{1}{3}$ for tension tests of cement and mortar. These constants are of course purely empirical and may or may not represent the true relation for different cements and other conditions of test.

The relation expressed by Eq. 2 given above is entirely rational. The two constants involved can readily be calculated so long as the strength at any two ages has been accurately determined. The determination of the constants is facilitated by plotting a curve to a logarithmic scale of ages. The writer has made no attempt to apply this method to a study of the strength of briquettes.

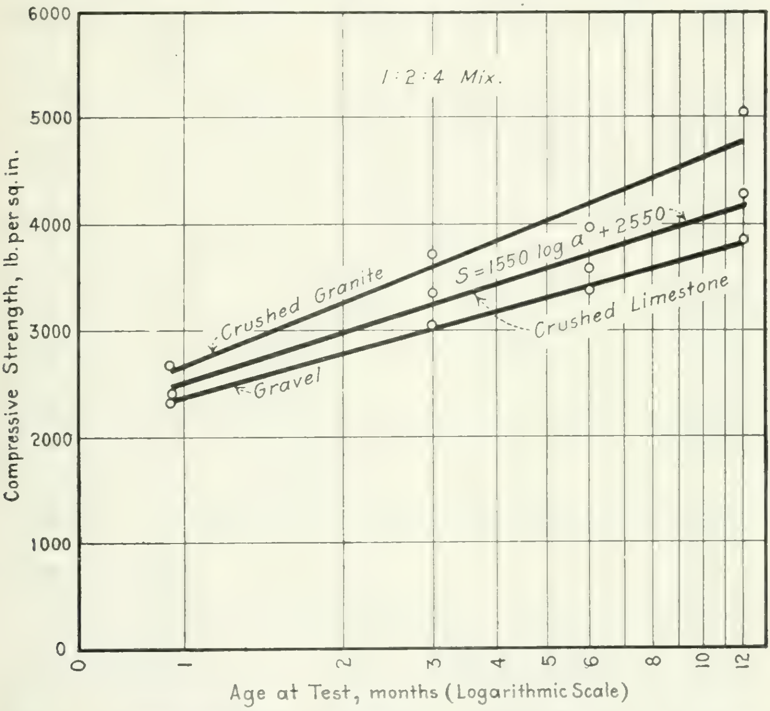


FIG. 15.—Compression Tests of Concrete. (*Bulletin No. 58*, U. S. Bureau of Standards, Table 8; 8 by 16-in. Cylinders. Certain lot numbers in the original table for which test data are incomplete have been omitted.)

The strength of concrete seems to increase indefinitely so long as it does not dry out. If the concrete is dried out and becomes wet only due to exposure to the weather, the change in strength will of course be much slower than if it is continuously saturated with water.

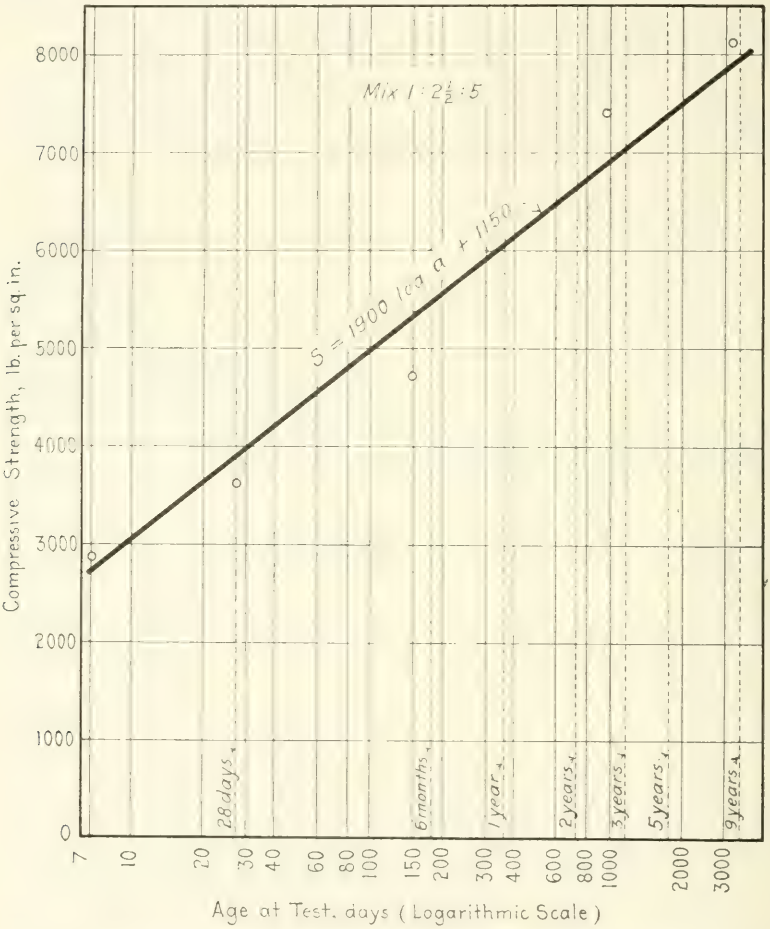


FIG. 16.—Compression Tests of Concrete. (Morsch, "Concrete-Steel Construction," translated by Goodrich; 20-cm. Cubes.)

Although a few series of tests described in the literature fail to show the continued increase in the compressive strength of mortar and concrete, we cannot avoid the conclusion that the logarithmic relation given in Eq. 2 expresses the true effect of age on the strength of concrete, so long as the concrete does not become thoroughly dry.

FURTHER CONSIDERATION OF BRIQUETTE TESTS.

In view of the very different age-strength relation found for concrete as compared with briquette tests of cement, it will be of interest to give some further consideration to the reasons for this difference.

As long ago as 1898, Prof. J. B. Johnson pointed out the great inequality in stresses which are developed in the minimum section of the briquette. As the result of analytical study of the problem, he reached the conclusion that the maximum stress in a briquette of the form now used in the United States is equivalent to about 1.54 times the minimum stress.[1]

As a result of the experimental determination of the stresses in a specimen of the form of the briquette, Mr. E. G. Coker found even greater inequalities in stress than were indicated by Johnson's analysis. Coker's results were derived from a study of the polarizing effect which resulted from stressing a specimen made of transparent celluloid. As a result of this experimental determination, he concluded that the highest stress in the minimum section of the briquette is 1.75 times the mean stress.[2] Fig. 17 shows the distribution of stress in a briquette according to these authors.

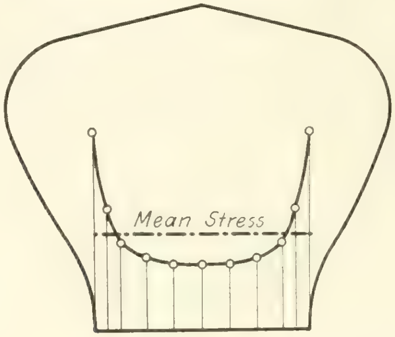
This inequality in the stresses in a briquette results, of course, from its shape and the method of applying the load to the test specimen. The concentrated loads which are applied by the clips at four points must be transmitted in a very short distance to the entire cross-section of the briquette. It can readily be seen that anything approaching a uniform distribution of the stress over the minimum section is impossible. It seems apparent that the relations which exist between loads and deformation in materials were not fully understood by the early experimenters.

The great inequality in the stresses in a briquette indicates a fundamental defect in the briquette as a standard test specimen. The inequality in these stresses will also enable us to account for the retrogression which occurs in the tensile strength of cement with the age of the test specimen. At the early ages the material has a low modulus of elasticity, hence the differences in stress between the outer edge and the middle of the section are not as great as would be the case if the material had a much higher modulus of elasticity. With a very rigid

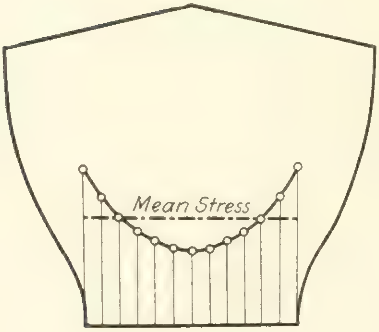
---

[1] See "The Materials of Construction," Fourth Edition, pp. 435,-437.

[2] See *Proceedings*, Inter. Assoc. Test. Mat., Second Section, 1912, paper 28.



According to
E. G. COKER.



According to
J. B. JOHNSON.

FIG. 17.—Distribution of Stress in a Briquette. (Coker, *Proceedings*, Inter. Assoc. Test. Mats., 1912, Paper No. 28; Johnson, "The Materials of Construction," 4th Ed., pp. 435–437.)

material the opportunity for an adjustment of stresses within the specimen is much less than in a material of low rigidity. We may expect that the inequality in stresses is much greater during the loading of the older briquettes than at early ages. In older briquettes a very high stress is developed at the edges of the section during the first stages of loading, hence a tearing action is produced which results in rupture at a lower average stress (lower total load) than would have been withstood at an earlier age when the lower rigidity permits of a more uniform distribution of stress.

That the rigidity of the specimen is largely responsible for the retrogression in the strength of briquettes is further shown by the fact that high early strength cements show retrogression at earlier ages than cements which attain their strength more slowly, and that the richer the mix the earlier retrogression begins.

In testing cement in tension, we are in reality subjecting a material of non-uniform and changing stiffness to eccentrically applied loads, which is contrary to sound engineering principles. It would be possible to obtain comparable results from specimens of this form in a material of constant modulus of elasticity, although we should at no time be obtaining the true breaking stress.

It should be noted that the American Society for Testing Materials has published a tentative specification and method of test for compressive strength of Portland-cement mortar.[1] The proposed method involves the testing of 1 : 3 standard sand mortar cylinders 2 in. in diameter and 4 in. in length at ages of 7 and 28 days. The compression test will no doubt come into general use and should eventually supplant the present standard briquette for acceptance tests of cements and for experimental work in studying the properties of cements and sand mortars.

---

[1] *Proceedings*, Am. Soc. Test. Mats., Vol. XVIII, Part I, p. 538.—ED.

THE NECESSITY FOR INSPECTION AND TESTING OF REFRACTORY BRICK.

By C. E. Nesbitt and M. L. Bell.

SUMMARY.

In this paper the authors call attention to the fact that no specifications for refractory brick of real value are in use at the present time, mainly because methods and tests developed for refractories are not suited for commercial inspection.

Tables are inserted showing irregularities in results obtained by the authors when testing commercial bricks.

Lack of uniformity of product is taken as proving the necessity for the inspection and testing of refractory brick, so that the consumer may be guaranteed a standard and uniform product.

THE NECESSITY FOR INSPECTION AND TESTING OF REFRACTORY BRICK.

By C. E. Nesbitt and M. L. Bell.

In nearly all industries, both raw material and finished products are bought and sold on specifications. These specifications vary from the most exacting to those in which nothing of importance is specified. The specifications for refractory bricks unfortunately come in the second class. This condition is very unsatisfactory, and it is felt that the time is rapidly approaching when specifications covering the important industrial qualities desired will have to be written.

A few simple specifications for refractories have been written. Some are in use, but they are of little practical value. Many tests advocated at the present time for refractories are not suited for use in specifications, as they do not show important qualities or are entirely too slow to be commercially applied. A manufacturer or consumer may handle daily from 50,000 to 150,000 bricks. If only one brick in every thousand is taken as a representative sample, it means that from 50 to 150 bricks must be sampled, tested and reported upon each day; hence, it is obvious that tests to be of commercial importance must be rapid, and to be of value must give definite values indicating the fitness or unfitness of the brick for the purpose intended.

The inspection of brick will probably have to proceed along lines similar to that of steel, which has been worked out most carefully and thoroughly. Steel is produced rapidly and in large quantities and is tested by the manufacturer throughout all its primary stages so that he knows the finished product will be of good quality. In like manner the brick manufacturer will have to test the brick during manufacture to insure uniform grinding, molding, drying and burning, resulting in consequent uniformity of product. A great deal of research work will have to be done by the brick manufacturer to determine what methods he should pursue, and like the steel manufacturer, he must know that his finished product will be of good quality.

Different industries require different physical properties in bricks. Specifications for brick should cover only those properties of the brick that are essential for some particular purpose. In testing bricks for the iron and steel industry we feel that the most important qualities can be satisfactorily determined by a few simple tests. In the case of silica brick, which are not ordinarily subjected to the action of slag, a spalling and a hot crushing test are considered sufficient; while clay brick should be subjected to load, spalling and slagging tests. These tests cover the particular qualities the brick must possess to give good service.

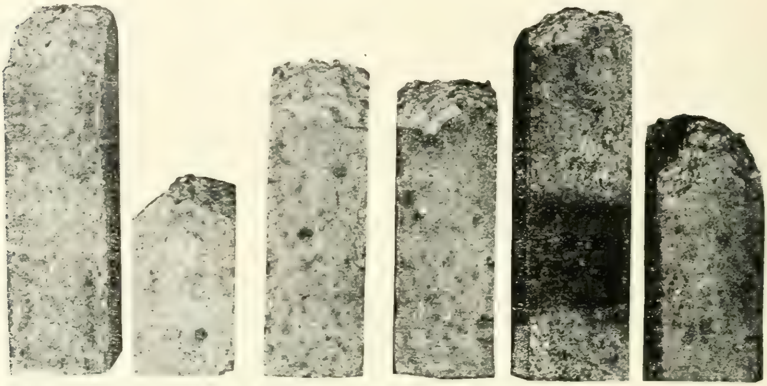
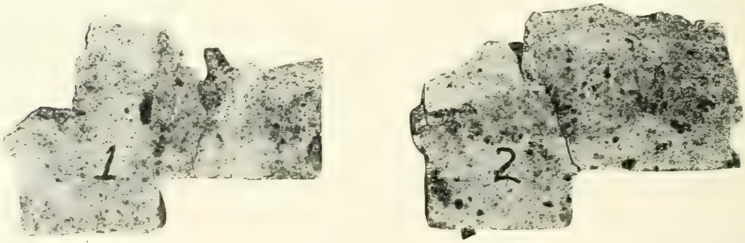


FIG. 1.—Illustration of Wide Variations in Spalling of a Standard 9-in. Silica Brick.



(*a*) Defective on Visual Inspection; Spalling Loss, 46 per cent. (*b*) Good; Spalling Loss, 32 per cent.

FIG. 2.—Showing Variation in Spalling Loss of Two 60-lb. Silica Shapes.

In addition to such tests it is, of course, very important that the bricks shall be subject to a careful visual inspection to guard against the acceptance of cracked or warped brick, poorly molded, off-size, or badly burned brick.

One does not have to go far in the testing of bricks to note the wide variations in the results, which reflect the variation in the bricks themselves. This is illustrated by the wide differences in the results of various tests given in the following tables.

SPALLING.

Spalling or resistance to sudden thermal change is a most important quality in bricks, especially silica bricks. It is a very common cause of failure. In Table I are shown the results of spalling tests on five successive shipments of one brand of silica brick. These tests were made in accordance with method given for "Spalling" in the appendix of our paper presented to the Society last year, entitled "Suggested Improvements in the Manufacture of Silica Brick."[1]

TABLE I.—LOSS BY SPALLING OF ONE BRAND OF SILICA BRICK.
ALL VALUES ARE EXPRESSED AS PERCENTAGE.

	Shipment No.				
	1	2	3	4	5
	11.72	13.39	12.65	11.24	14.96
	13.95	15.53	13.44	12.45	21.01
	15.08	16.22	17.60	13.94	21.96
	19.47	20.38	19.01	19.53	23.93
	22.39	21.84	28.29	21.43	28.11
	24.12	23.48	23.32	22.51	29.47
	25.95	24.31	32.95	22.64	29.76
	32.45	24.80	34.03	24.81	30.88
	39.84	37.25	35.95	27.39	31.73
	40.80	42.27	41.31	30.00	38.34
Average..........	24.58	23.95	25.86	20.59	27.02

It will be noted that the spalling loss on bricks from the same shipment varied from 11.72 to 40.80 per cent in one case and 13.39 to 42.27 per cent in another shipment, although the average for all the shipments was about 25 per cent. Such variations are due to lack of uniformity in grinding, molding and general workmanship, all of which can be largely eliminated with proper care. Figs. 1 and 2 show typical examples of the variations found in making spalling tests. Figs. 3 and 4 illustrate one cause of failure in spalling tests.

---

[1] *Proceedings*, Am. Soc. Test. Mats., Vol. XVII, Part II, p. 468 (1917).

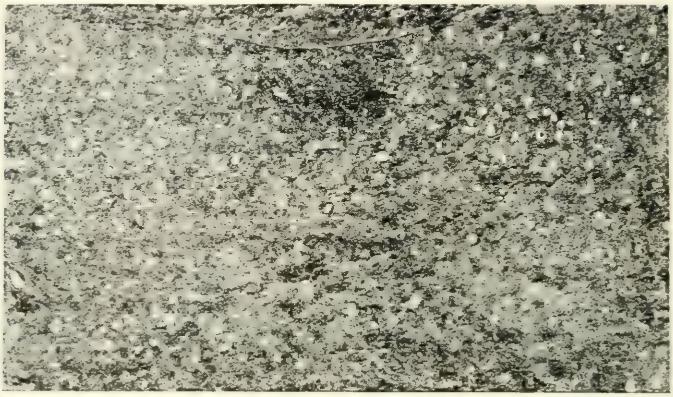


FIG. 3.—Example of Variation in Internal Structure of Silica Shape Which by Visual Inspection Would Have Been Considered Satisfactory.—Note holes and cracks due to improper molding, which would have been detected by a spalling test.

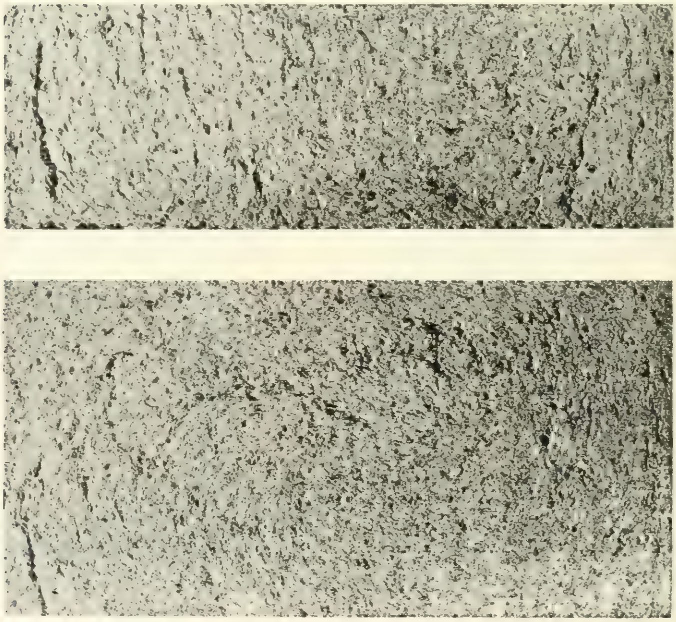


FIG. 4.—Two First-Grade Refractory Brick showing Poor Texture which often Causes Premature Failure.

CRUSHING TESTS.

Similar lack of uniformity has likewise been shown by the crushing test. A series of tests were made on a number of commercial bricks, the object being to determine the variation in actual crushing strength of bricks from the same shipment and the relative crushing strength of different brands of brick when tested at different temperatures.

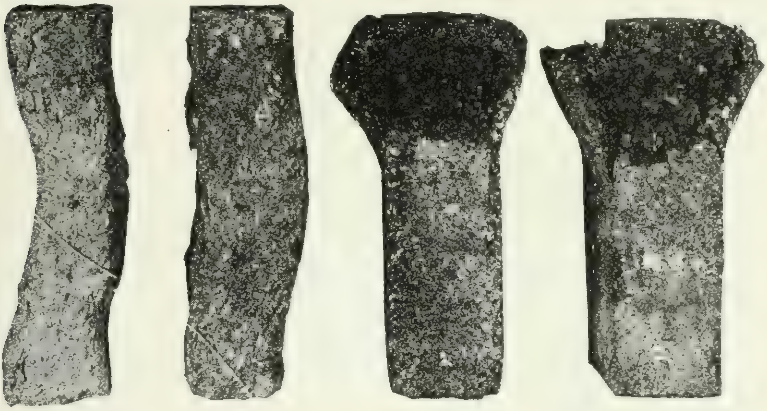

At 1000° C. At 1350° C

FIG. 5.—Examples of Deformation of Clay Brick as Result of Crushing Test.

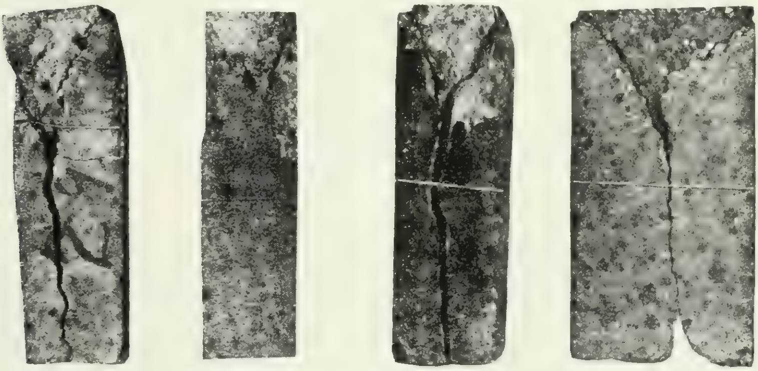


FIG. 6.—Typical Examples of Fractures of Silica Brick as Result of Crushing Test.

TABLE II.—CRUSHING TESTS ON CLAY AND SILICA BRICKS.

Brick.	Crushing Strength, lb. per sq. in., at			Load, lb. per sq. in., Required to Cause First Deformation at	
	30° C.	1000° C.	1350° C.	1000° C.	1350° C.
Clay A	850	2055	662	....	364
	1143	2068	828	....	513
	1254	2639	1013	806	540
	1292	2913	1112	1111	556
	1351	2981	1307	1120	563
	1567	3086	1343	1458	573
	1812	3132	1581	1671	583
	2091	3135	1657	1711	585
	2469	3182	1683	1835	625
	2853	3735	1708	1956	861
Average.....	1668	2892	1289	1458	576
Clay B	1274	3686	757	No deformation before fracture.	105
	1341	3698	803		430
	1387	3843	803		649
	1442	4190	814		649
	1695	4259	928		706
	1698	4376	980		725
	1843	4559	1017		752
	1954	4559	1018		769
	2196	4672	1171		911
	2603	4739	1188		991
Average.....	1743	4258	948		669
Silica C	2921	762	820	No deformation before fracture.	
	3286	1116	1390		
	3454	1217	1736		
	3657	1775	1743		
	3837	2227	1766		
	3911	2236	1861		
	4154	2435	1961		
	4164	2720	2221		
	4452	2781	2378		
	5810	4219	2434		
Average.....	3965	2148	1831		
Silica D	1037	1026	547	No deformation before fracture.	
	1320	1051	669		
	1499	1235	702		
	1548	1248	783		
	1701	1308	822		
	1738	1614	912		
	1912	1693	938		
	1974	1696	945		
	2057	1723	1060		
	2222	3274	1120		
Average.....	1700	1587	850		
Silica E	1317	858	465	No deformation before fracture.	
	1432	1137	551		
	2078	1205	597		
	2117	1217	675		
	2530	1285	719		
	2548	1333	1152		
	2823	1389	1285		
	2967	1498	1289		
	3158	1563	1541		
	3988	1895	....		
Average.....	2496	1338	919		
Silica F	1420	933	275	No deformation before fracture.	
	1643	949	283		
	1658	1062	299		
	1760	1151	318		
	1795	1191	427		
	1911	1237	458		
	1941	1240	470		
	2250	1574	475		
	2479	1596	492		
	2513	1877	808		
Average.....	1937	1281	430		

Six different brands were represented, of which two brands were clay bricks and four silica bricks, all of supposedly good quality. In sampling, all bricks of each individual make were chosen from a single order and represent several cars. Only bricks judged to be good by visual inspection were taken for the test. The bricks were prepared and tested as described in the appendix of our paper before the Society last year, referred to above.

It will be noted that the total crushing strength of clay brick at 1000° C. is apparently higher than the strength at 30° C., but this is misleading. At elevated temperatures clay bricks start to splinter off before being completely crushed. The first splintering or deformation is recorded in the right-hand columns of the table and show that the results obtained at first deformation at 1000° C. are lower than at 30° C., which is in accord with the results obtained on silica bricks; namely, the higher the temperature, the weaker the brick. (Figs. 5 and 6.)

While both clay and silica bricks are represented in Table II, we do not favor the hot crushing test for clay brick, the load or ball impression test being more suitable.

SLAG PENETRATION.

Lack of uniformity of product is not shown by the spalling and crushing tests alone, but also by the variations in slag penetration. This is largely governed by lack of uniform structure, due to lack of uniform grinding, molding and burning. This condition is best illustrated by Figs. 7 and 8.

CONCLUSION.

The results of a few tests such as we have shown here point out the necessity for the inspection of refractory brick. Inspection and testing seem to be the only means of obtaining brick of uniform quality. At present the consumer is forced to accept brick without direct information as to their quality. Many instances can be cited where brick of poor quality have been accepted without knowledge of their inferiority, resulting in the premature failure of the furnace or other structure in which they were used and causing an unnecessary loss of money, time and production. Much of this loss could have been avoided if the bricks had been tested before being put into service.

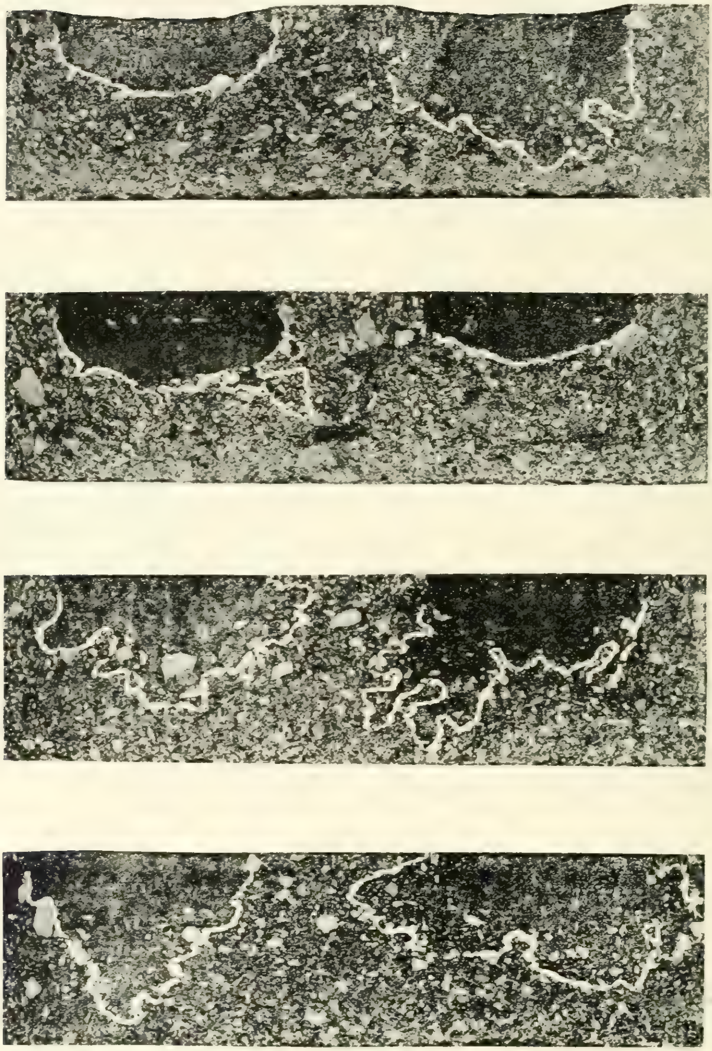


FIG. 7.—Typical Examples of the Manner in Which Slag Penetration Follows Lines of Weakness in Brick Structure.

Before the bricks are shipped by the manufacturer a great deal can be accomplished by careful visual inspection, by means of which all bricks irregular in shape, off size, fire cracked, improperly molded, and of poor general appearance would be eliminated. If proper care is taken in the brick plant this rejection need not be a very large percentage of the output. A storage shed should be provided so that bricks may be taken from the kiln and stored for a period of time sufficient for this inspection and the necessary tests.

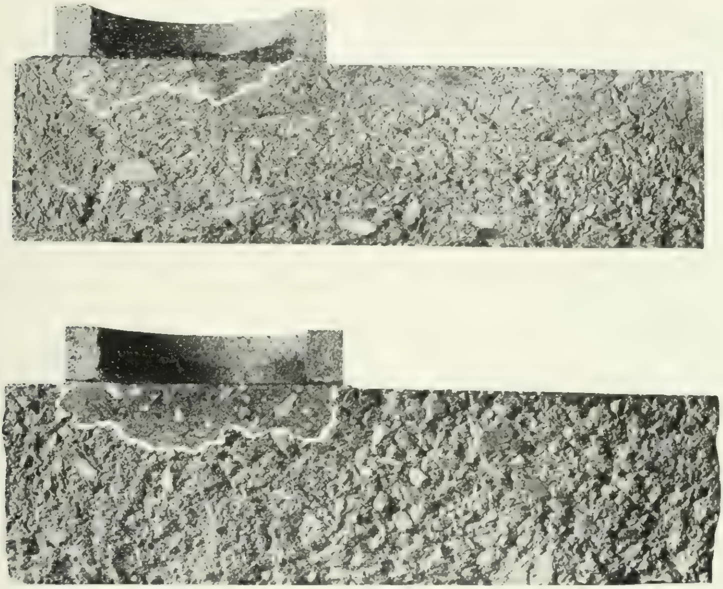


FIG. 8.—Two Bricks from Same Shipment.—Note difference in texture and resulting variation in slag penetration. Upper brick, 1.13 per cent; lower brick, 2.13 per cent.

The present methods of making refractory brick do not produce a uniform product. The consumer is powerless to change present methods. To secure greater uniformity, he must adopt specifications for brick with the end in view, not to reject material which is good, but to guard against the acceptance of that which is bad.

DISCUSSION.

Mr. Howe. MR. RAYMOND M. HOWE.—The authors have proved very conclusively that fire brick are subject to variations. This has been realized by the manufacturers for some time and improvements are being made constantly for the purpose of producing more uniform ware. More care is taken in grinding, modern dryers are being gradually installed, machines are used which do not produce laminations in the brick, and the older kilns are being replaced by those which operate with more uniformity of temperature.

Certain limitations, however, must be realized, for the manufacture of refractory materials is not a chemical process but a mechanical one. The raw materials, especially under present conditions, cannot be given chemical treatment but must be used as they are found in nature.

The authors state that one sample should be taken from each one thousand brick for testing purposes, which will necessitate the testing of from 20 to 250 bricks a day at the plants. The necessity of such extensive testing has hardly been established. The reasons stated briefly are as follows:

When a manufacturer decides to use a certain deposit of clay he is necessarily restricted by the properties of this clay with respect to its possible uses. In a short time he realizes its possibilities and then decides upon his method of manufacture. Experimentation on grinds, mixes and processes soon tell him what methods he should follow. These conclusions are reached by means of slag tests, spalling tests, tests for refractoriness, and such others which bear upon the use for which the brick are designated. His particular product when made by that process exhibits certain general properties consistently, being dense or porous, laminated or uniform, of high or low refractoriness, tough or brittle, etc.

When the process is controlled, the only remaining variable is the raw material. This must be watched rather carefully but even then not so closely as has been indicated. One hundred thousand bricks represent such a small volume of clay or ganister **Mr. Howe.** that one test in this number is sufficient for checking the uniformity of that product.

The consumer, although judging brick from a different standpoint, faces very nearly the same problem. He wishes a brick of certain structure and refractoriness. It must meet certain conditions. He therefore surveys the field and in a short time is able to select a few suitable brands. Proper testing may eliminate some of these. From that time, his problem also becomes one of control and, above all, he should keep in touch with any changes which may be made at the plant. One man, by doing this, can learn more than a dozen men can learn from laboratory tests. I do not mean by this, however, that all testing should be eliminated, but that it becomes very much simplified. If the bricks deteriorate, principally due to abrasion, abrasion tests may be run from time to time. If subjected to very high temperatures, its refractoriness should be watched; if subjected to repeated heating and cooling, the spalling test will be of value. A silica brick can be controlled by specific gravity tests and visual inspection, the former indicating the completeness of the burn and the latter defects in manufacture. In this way the problem of control is not so serious as the authors would lead one to believe. Radical changes do not occur in a day, and if the shipments tend to become of poorer quality for any particular use they can be halted then rather than every day, which would be the case if stored in the manner suggested.

In conclusion, I wish to emphasize that certain things must be realized:

1. That the raw material cannot be altered;
2. That the process is purely mechanical;
3. That the general properties of certain brands remain practically the same;
4. Because of this and of the fact that the clay itself cannot be spoiled in manufacture, as can iron or steel, close checks are not necessary.
5. Close cooperation between the manufacturer and the consumer will eliminate many difficulties and will make for their mutual advantage.

Mr. Unger. MR. J. S. UNGER.—The authors of the paper touch upon a very important point in brick quality, when they refer to lack of uniformity in commercial brick. Much could be added to give this greater weight. A few examples will suffice to make it clearer.

I have seen a single high-grade 9-in. fire brick show six times greater loss on abrasion at one end as compared with the other, when tested at 1350° C. Single bricks of either fire clay or of silica have shown 100 per cent variation in slag penetration at points not over 2 in. apart on the same side of the brick, at the same time and under the same conditions of testing. A brick, cut into halves transversely and tested on opposite faces, may show four times as much slag penetration on one face as on the other. Messrs. Nesbitt and Bell illustrate this point in Fig. 8 of their paper.

This same lack of uniformity is shown by spalling, crushing and some other tests and is not confined to an occasional brick, but is so prevalent that it can be stated that one brick out of every three is abnormal, the other two do not check one another, nor will any of the bricks show approximate results at both ends.

The authors show great variations in spalling in their Table I, and in crushing in the third column of Table II. These results are startling, but they explain why such poor service is at times obtained from brick; in fact, they make one wonder that brick ever stand up in service.

In a furnace wall where one brick is resting on another, the whole being bound together and not subjected to an excessive load, the lack of uniformity in brick is not easily detected and may not cause the failure of the structure. If used in a roof or in the arches of flues where each brick acts as a single unit, the poor or non-uniform brick measures the life of the whole structure.

The trade requires a more uniform brick. There is not a great demand for specially refractory brick made of comparatively rare materials at considerably increased cost, but there is an urgent demand for uniform brick made of easily available materials. More uniform quality can be attained by better methods of manufacture. Some brick plants may have to change many of their methods and ideas. It is to be hoped that the maker will accomplish such changes without being forced to make brick to a specification. **Mr. Unger.**

The question may be summed up in this way: The present brick are not of uniform quality. The customer must have uniformity in quality, to obtain uniformity in service.

MR. J. M. MCKINLEY.—Mr. Unger speaks of forcing the manufacturer to new methods. This, it seems to me, is rather beside the point. There is not a manufacturer represented to-day in modern refractories who is not more than anxious to reach the ideal that Mr. Unger outlines. There is one point to be brought up in this discussion which is entirely in line with the actual facts in the case. Processes can be manipulated in the manufacture of fire brick in a number of ways. The occurrence of clay in the ground can not, however, be manipulated in any way, shape, or form. In iron ore and in a wide variety of metallurgical substances, a certain substantial regularity as to the chemical content and physical character of the raw material can be found; for example, the ores of the lake region may run with remarkable regularity. Fire clay does not run in this manner. Taking as a case in contrast, the clays of the Clearfield region, which are as typical of American conditions as those of any region we might name, an astounding variation, judged by present technical standards, will be found in the same vein and in a single acre. I have seen at no place in the papers so far developed in the consideration of this subject, nor have I had brought to my attention, any mention of this fact. This variation appears frequently in a matter of a few feet in a vein. With both a vertical and lateral variation of this kind standardization and control are impossible, except by methods involving enormous and non-productive costs. **Mr. McKinley.**

It seems to me, from a constructive standpoint, that no specifications can be successfully applied until they reckon with this variation. Mr. Howe has spoken of the fact that this is not a chemical proposition. I want to support this statement as strongly as I can from a manufacturing standpoint. A real working basis complete within itself has eluded us entirely within the last few years, and the specifications proposed must be considered tentative until this added factor of variation has received proper consideration.

SILICA CEMENT.

BY ROBERT J. MONTGOMERY.

SUMMARY.

In this paper an attempt is made to cover the subjects of composition and testing of the silica cement now in general use. It is pointed out that the refractoriness depends largely upon the alumina-silica ratio and that the limits of composition are easily established by referring to the eutectic curve between alumina and silica. The effect of size of grain is discussed. The crushing strength, porosity, apparent specific gravity, shrinkage or expansion and hardness are given for a typical sample burned to various temperatures up to 2800° F. Data on the safe operating temperature for cements are given.

In conclusion a list is submitted which will give much important information as to the quality of a cement.

SILICA CEMENT.

BY ROBERT J. MONTGOMERY.

Within the last two or three years a number of investigations on the properties of silica brick have been published, including methods of manufacture and testing, but little or nothing has been published on the subject of a cement or mortar to be used in laying such brick. It is not necessary to emphasize the importance of the cement which is laid between the silica brick or shapes and which is exposed to the same conditions of load, temperature, corrosion, etc., as the brick itself. In this paper an attempt is made to cover in a general way the subjects of composition and testing of the silica cement that is now in general use.

PROPORTIONING OF SILICA CEMENT.

Probably the ideal cement is one of the same composition as the brick, since then such properties as the coefficient of expansion, drying and burning shrinkage, etc., could be largely disregarded. In fact, present-day practice in the manufacture of silica cement approaches this as nearly as possible in the use of the "ganister mud" used in the making of silica brick; but owing to its lack of plasticity, the "ganister mud" must be treated by the addition of clay and by grinding, so as to allow easy working with a trowel when mixed with water to form a mortar. In a word, silica cement is a mixture of ground ganister rock and clay. The ganister may be freshly ground ganister rock, green bricks which have been discarded on account of defective molding, or ground "bats," which are cull brick or shapes. These green bricks or burned bats contain about 2 per cent of lime, which is added in the manufacture of the original brick.

The proportions used vary considerably; the clay content is usually from 15 to 35 per cent, while the proportion of ganister rock to bats is one to one. When green bricks are used, it is usually in place of the ganister rock.

The effect of varying the clay content is well understood and will be considered later. The correct proportioning of burned bats and unburned ganister or green brick is not so easily determined, although it is recognized that on heating to operating temperatures the ganister or green brick will expand more than the burned bats, owing to the change of the quartz to cristobalite. In the burned bats a large part of this change has already taken place. The proportions are more often determined by the amount of cull material on hand at the brick plant than by any desire to control the expansion of the cement.

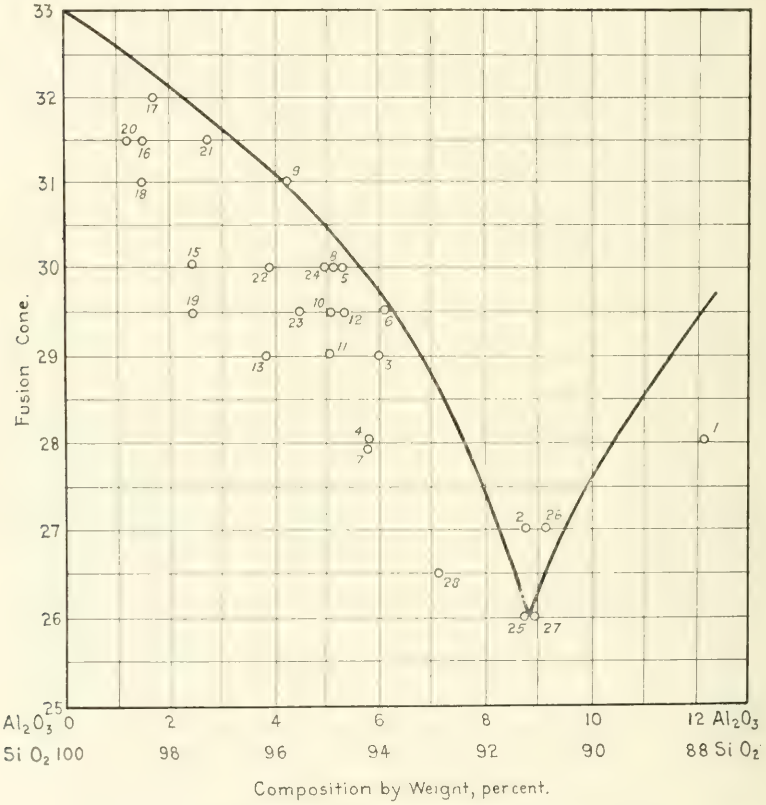


FIG. 1.—Portion of $Al_2O_3-SiO_2$ Eutectic Curve (Sosman).
Values plotted from Table I.

To the writer's knowledge this phase of the subject has not been investigated to any extent.

REFRACTORINESS AND PLASTICITY OF SILICA CEMENT.

Effect of Clay Content.—The clay content is very important, for it affects to a marked degree the refractoriness and plasticity or working properties of the cement. As is well known, alumina (which is introduced in the clay) is a very active flux when in contact with silica; and in a silica cement it is the factor which governs the fusion point, as the other fluxes remain quite low in amount and quite constant when high-grade materials are used. The amount of lime introduced in the burned bats or green brick is too small to have much effect on the fusion point and will be constant if a constant percentage of bats is used. In determining the effect of a given percentage of clay the eutectic curve between alumina and silica as given by Sosman[1] is of considerable value. A portion of this curve is shown in Fig. 1 and indicates the limit of refractoriness that may be attained by a cement containing a given percentage of alumina introduced from clay or already in the ganister rock as an impurity. On making fusion tests covering a great many samples of cement, it was found that if all of the materials used are of good quality the fusion point will not fall more than two cones below this theoretical line. By using a combination of the fusion test and analysis, a cement of any desired fusibility up to the melting point of silica itself may be proportioned. Table I gives a list of some twenty-seven commercial cements with analysis and fusion point. The values plotted in Fig. 1 are taken from the last three columns of this table. The value for percentage of alumina is obtained by adding the values in the second and third columns and calculating the percentage of each based on $Al_2O_3+SiO_2=100$. This gives the true ratio between them.

The desired refractoriness of the cement depends upon the conditions of use, such as the temperature, load, etc., and this can best be determined by trial. It should be borne in mind that the clay corrects one evil and introduces another. If the

---

[1] *Transactions*, American Ceramic Society, Vol. 15, p. 486.

TABLE I.—ANALYSIS AND FUSION POINTS OF COMMERCIAL CEMENTS.

Test No.	Analysis.			Calculated Values.		Fusion Cone.
	SiO_2, per cent.	Al_2O_3, per cent.	Fluxes and Ignition Losses, per cent	SiO_2, per cent.	Al_2C_3, per cent.	
1......	83.30	11.68	5.02	87.8	12.2	28
2......	87.80	8.27	3.93	91.2	8.8	27
3......	90.30	5.84	3.86	94.0	6.0	29
4......	90.71	5.50	3.79	94.3	5.7	28
5......	92.00	5.18	2.82	94.7	5.3	30
6......	91.44	5.76	2.80	93.9	6.1	29½
7......	91.56	5.46	2.98	94.3	5.7	28
8......	90.58	4.99	4.43	94.7	5.3	30
9......	92.14	4.13	3.73	95.7	4.3	31
10......	92.30	4.82	2.88	95.0	5.0	29½
11......	92.50	4.75	2.75	95.0	5.0	29
12......	91.64	4.86	3.50	94.7	5.3	29½
13......	94.16	3.80	2.04	96.2	3.8	29
14[a].....	.....	...	....	....	...	..
15......	94.16	2.12	3.72	97.6	2.4	30
16......	94.30	1.32	4.38	98.5	1.5	31½
17......	93.58	1.54	4.88	98.3	1.7	32
18......	94.90	1.50	3.60	98.5	1.5	31
19......	94.00	2.43	3.57	97.6	2.4	29½
20......	93.00	1.03	5.97	98.7	1.3	31½
21......	91.62	2.60	5.78	97.3	2.7	31½
22......	92.96	3.73	3.31	96.1	3.9	30
23......	90.48	4.12	5.40	95.5	4.5	29½
24......	92.00	4.85	3.15	95.0	5.0	30
25......	88.30	8.27	3.43	91.3	8.7	26
26......	87.16	8.65	4.19	90.9	9.1	27
27......	87.31	8.24	4.45	91.3	8.7	26
28......	89.31	6.62	4.25	92.9	7.1	26½

[a] Test No. 14 not completed.

clay content is too low the plasticity will be so low that it will be practically impossible to lay brick with full joints, as the water will run out of the cement immediately into the brick on which it is placed and will act more like wet sand than a workable mortar. If the clay content is too high the fusion point will be lowered and the burning shrinkage will be excessive, causing a settling of the walls and loss of alignment. Any sagging of the walls in the hotter parts of a furnace is very objectionable, especially in coke oven practice. It is necessary then to establish the required refractoriness which will stand the maximum furnace temperature without undue softening and shrinkage, and still be plastic enough to allow good work in laying the brick.

Effect of Fine Grinding.—The plasticity of the cement can be controlled to some extent by fine grinding. The finer grained material can be more easily spread with a trowel, but if too fine, vertical parting cracks will appear in the joints, resulting in leaks through the walls. Extreme fineness also tends to increase the drying and burning shrinkage. The two sieve tests given below show the usual limits:

TYLER STANDARD SIEVE.	A	B
Retained on 20 mesh, per cent	1.6	0.0
" " 48 " "	24.7	7.3
" " 100 " "	37.2	21.3
" " 200 " "	12.8	10.3
Through 200 " "	23.7	61.1
	100.0	100.0

The finer cement, B, requires much more time in grinding and it is a question whether it is commercially practicable with the grinding mills now used. It would almost be necessary to resort to the ball mill.

PROPERTIES DURING DRYING AND BURNING.

Next to the refractoriness and plasticity the most important properties are those developed at various temperatures below the fusion point. These include drying, burning and total shrinkage, porosity, apparent specific gravity, crushing strength, hardness and safe operating temperature. A cement of the following composition was tested, and the various properties determined are given in Table II.

ANALYSIS.

SiO_2	90.94 per cent
Al_2O_3	5.03 "
Fe_2O_3	0.52 "
CaO	1.60 "
MgO	0.00 "
Ignition loss	1.74 "
Moisture	0.15 "

SIEVE TEST.

Retained on 20 mesh	0.0 per cent
" " 48 "	12.2 "
" " 100 "	34.7 "
" " 200 "	16.8 "
Through 200 "	36.3 "
	100.0

The fusion point was Cone 29.

TABLE II.—PROPERTIES OF SILICA CEMENT AT VARIOUS TEMPERATURES.

Temperature, deg. Fahr.	Crushing Strength, lb. per sq. in.	Porosity, per cent.	Apparent Specific Gravity.	Shrinkage, per cent.		Hardness: Scratched by
				Total.	Burning.	
Room...	61	Disintegrated[b]	Disintegrated[b]	1.2	....	1:5-H Pencil
212....	90	"		1.2	....	1 " "
600....	110	"		0.2	0.8 (Exp.)	1 " "
1000....	123	"	"	0.6	0.8 "	1 " "
1200....	185	"	"	0.2	1.0 "	1 " "
1400....	140	Slightly disintegrated	Slightly disintegrated	0.3	0.9	2:Lead
1600....	320	33.4	2.45	0.0	1.0 "	3 Copper Wire
1800....	447	32.8	2.44	0.0	1.1 "	3 " "
2000....	700	33.2	2.44	0.0	1.1 "	4:Steel Nail
2200....	1227	31.2	2.42	0.2	0.8 "	5:Glass Tubing
2400....	4000[a]	24.6	2.33	0.9	0.7 "	6:Harder than 5
2600....	2700[a]	30.0	2.38	1.8	1.0 (Shr.)	6 " " 5
2800....	3385[a]	31.5	2.41	3.9	2.8 "	6 " " 5

[a] These cubes were crushed on a 50,000-lb. machine. The load was so small for the machine that only approximate results were obtained. The high point at 2400° F. seems to be correct.

[b] Disintegrated when boiled in water.

The drying and burning shrinkage was measured on small test bars; the crushing strength test was made cold, on 1-in. cubes burned to the temperatures indicated in Table II. The apparent specific gravity, porosity and hardness were determined on similar cubes.

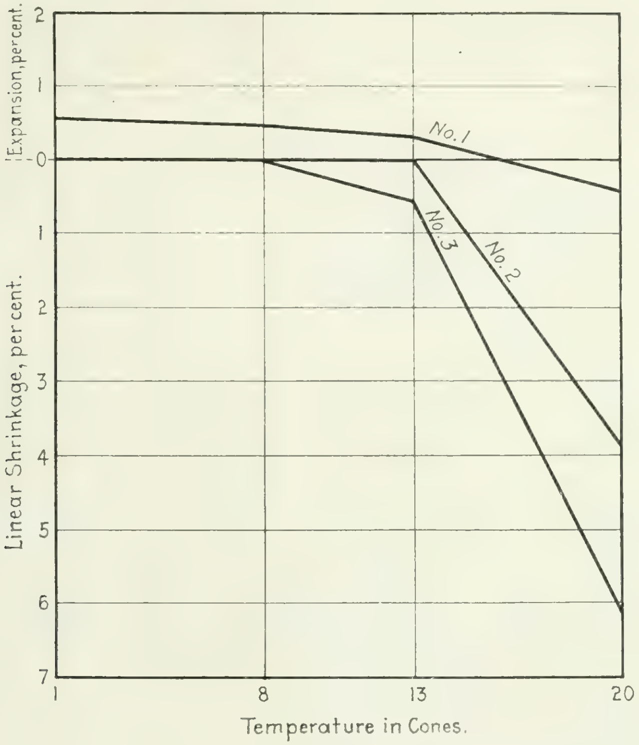


FIG. 2.—Variations in Burning Shrinkage, Plotted from Table III.

Drying and Burning Shrinkage.—Drying shrinkage is objectionable but cannot be avoided, as the clay present must shrink. The amount of shrinkage will vary from 0.5 to 2.0 per cent, depending upon the fineness of the grinding and the amount of clay substance in the mix. The burning shrinkage is low until about cone 13 is reached. Above this temperature it increases very rapidly and will depend as much on the amount and condition of the base fluxes present as on the alumina content. Table III gives results on three samples showing the variations to be expected. These are also shown graphically in Fig. 2.

TABLE III.—PERCENTAGE OF EXPANSION ON SHRINKAGE DUE TO BURNING.

SAMPLE NO.	CONE 1.	CONE 8.	CONE 13.	CONE 20.
1.........	0.5 (exp.)	0.4 (exp.)	0.3 (exp.)	0.4 (Shr.)
2.........	0.0	0.0	0.0	3.8 "
3.........	0.0	0.0	0.5 (Shr.)	6.1 "

There is a tendency for silica cement rather low in clay to show an expansion of about 0.5 per cent at the lower cones. This observation was made on small test bars burned in the laboratory, but in all probability it will hold for commercial installations. As the temperature increases the shrinkage of the clay overcomes the expansion of the silica and at cone 20 the burning shrinkage may vary from about 0.4 per cent to as high as 6.0 to 7.0 per cent. This will give a total shrinkage, including drying and burning, of 1.0 up to 8.0 or 9.0 per cent.

The burning and total shrinkage curves of the cement recorded in Table II are plotted in Fig. 3.

Porosity and Apparent Specific Gravity.—These determinations will aid in differentiating between cements, but they do not have the practical application of the shrinkage determination. The porosity will vary from about 30–35 per cent at cone 1 to 15–30 per cent at cone 20, depending upon the composition of the cement. The apparent specific gravity will vary from 2.40–2.45 at cone 1 to 2.20–2.38 at cone 20, depending upon the composition.

Fig. 4 shows the variation of the porosity and apparent specific gravity of the cement referred to in Table II with the burning temperatures. The increase in porosity and specific gravity above 2400° F. with this sample was unexpected and the cause is not known. Such an increase usually indicates overfire and swelling, but overfire would reduce the shrinkage and seldom increases the apparent specific gravity.

Strength and Hardness.—The hardness and crushing strength curves of the sample tested are plotted on Figs. 3 and 4 from the data in Table II. The hardness increased as the temperature is raised to 2800° F., while the crushing strength reached a maximum at 2400° F. The strength was quite low until 1600° F.

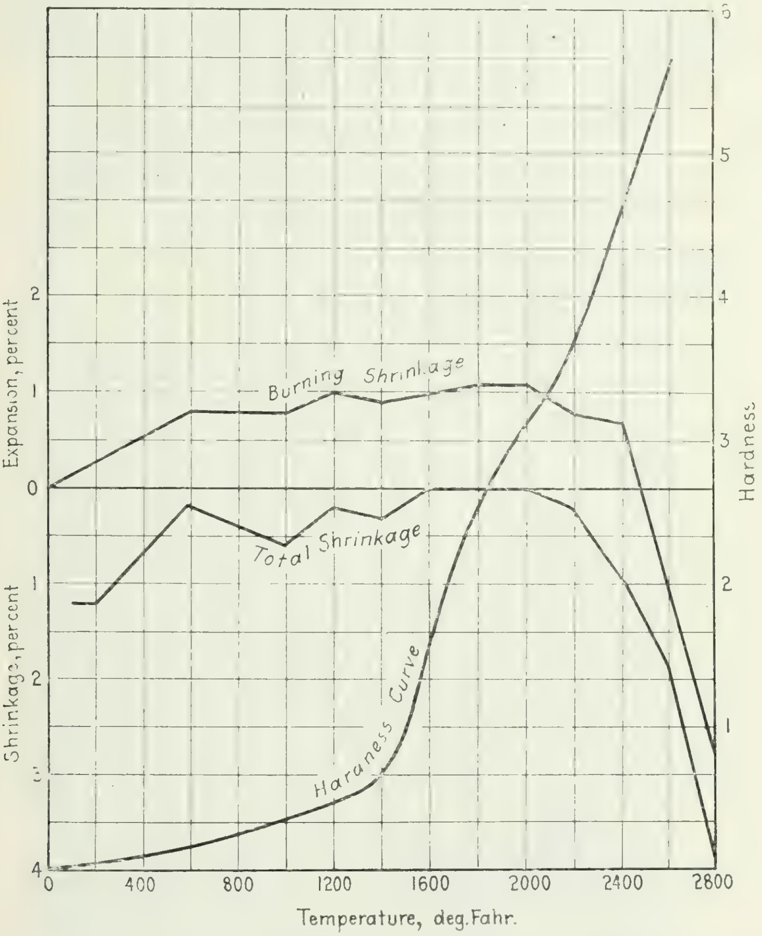


FIG. 3.—Effect of Temperature on Shrinkage and Hardness, Plotted from Table II.

is reached and then increased rapidly. The values above 2000 lb., as noted in Table II, are only approximate, as the testing machine used was not adapted to the load. As most furnace construction is designed to give stresses of not over 25 lb. per sq. in., the cement will easily carry the load at all temperatures within its working limit.

Safe Operating Temperature.—In order to obtain some information relating to safe operating temperature, three cements were molded into brick form 9 by $2\frac{1}{2}$ by $2\frac{1}{2}$ in. in size, placed on end in a small furnace, and heated to approximately their melting points and held for 24 hours.

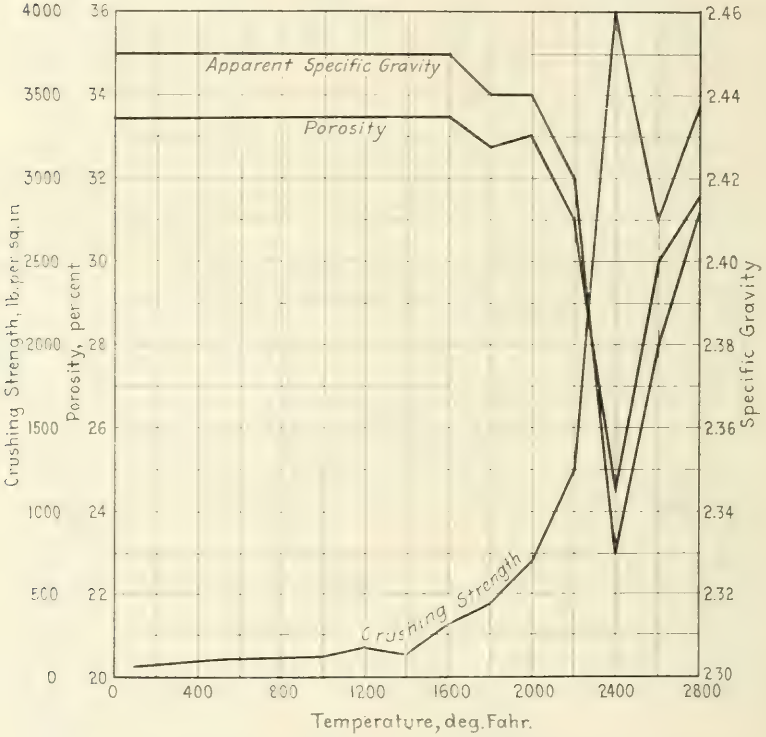


FIG. 4.—Effect of Temperature on Crushing Strength, Porosity and Specific Gravity, Plotted from Table II.

One was a cone-31 cement. It melted very slowly at 2800° F. and slumped under its own weight, being too soft to be of value as a cement. It stood at 2700° F. without showing any tendency to deform.

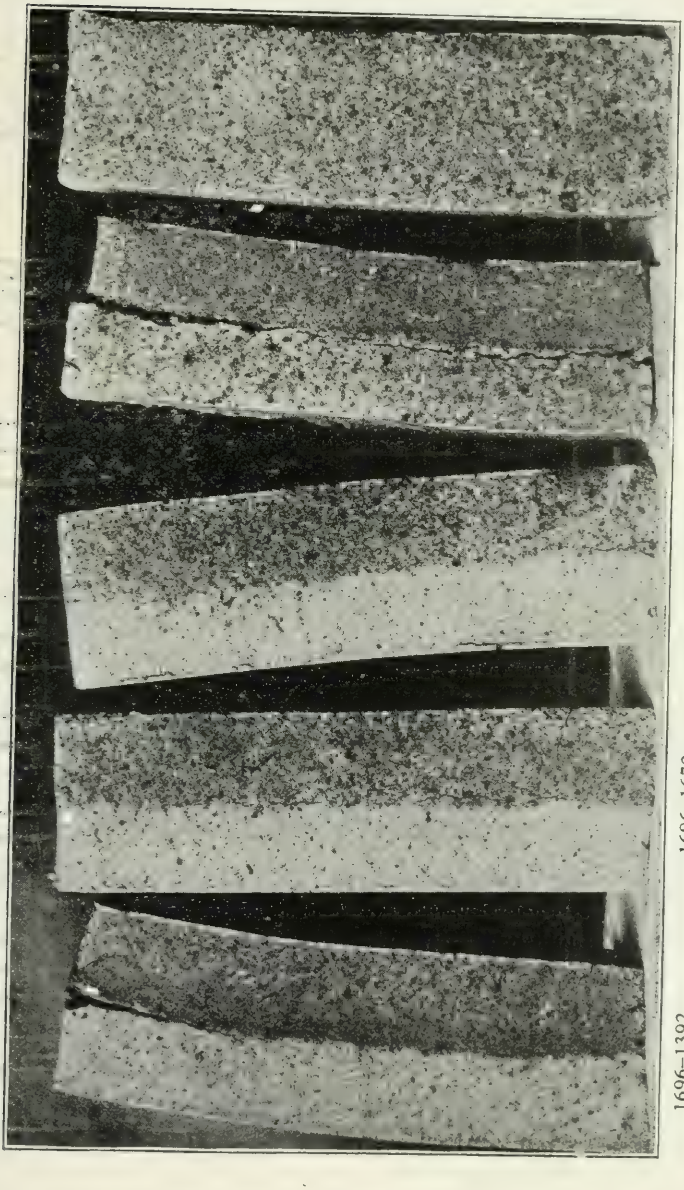


FIG. 5.—Illustrating Method of Comparing Burning Behavior of Two Cements.

The second was a cone-30 cement. It softened badly at 2800° F., slumping to the bottom of the furnace under its own weight. At 2700° F. it showed no tendency to deform after 24 hours at this temperature.

The third was a cone-28½ cement. It slumped to the bottom of the furnace under its own weight at 2700° F., but held 24 hours at 2600° F. without softening.

TESTING SILICA CEMENT.

The following tests will give quite complete information concerning a silica cement:

1. Analysis;
2. Fusion cone;
3. Sieve test using 20, 48, 100 and 200-mesh Tyler standard sieves;
4. Drying shrinkage;
5. Burning tests at several cones as Nos. 1, 8, 13 and 20; determine (*a*) Burning shrinkage;
    (*b*) Total shrinkage,
    (*c*) Porosity,
    (*d*) Apparent specific gravity.

For control work these tests may be narrowed down considerably. A very good way to compare the burning behavior of two cements is to make a test bar, about 1½ by 1¼ by 5 in. long, composed of two layers, the lower ¾ in. of a standard cement and the upper ¾ in. of the cement to be tested. The joint between the two should be well worked by roughening the surface of the lower layer before the upper one is put on. This "double bar" is then burned to the desired temperature (say cone 20) and the difference in expansion and contraction will be shown by the appearance of the bars. Fig. 5 illustrates the results of such a test. By changing the composition of the cement corrections may be made in the test batch until it agrees with the standard.

THE STANDARD SAYBOLT UNIVERSAL VISCOSIMETER.

By Winslow H. Herschel.

SUMMARY.

In a paper presented at the last annual meeting,[1] the method was described for determining an equation giving the relation between the readings of certain Saybolt Universal viscosimeters and absolute viscosity. As a result of the work described in the present paper, a similar equation for instruments of standard dimensions was found to be

$$\text{Kinematic Viscosity} = \frac{\text{Viscosity, in poises}}{\text{Density, g. per cc.}} = 0.00220\, t - \frac{1.80}{t},$$

in which t is the time of discharge in seconds.

---

[1] "Determination of Absolute Viscosity by the Saybolt Universal and Engler Viscosimeters," *Proceedings*, Am. Soc. Test. Mats., Vol. XVII, Part II, p. 551 (1917).

THE STANDARD SAYBOLT UNIVERSAL VISCOSIMETER.

BY WINSLOW H. HERSCHEL.

In previous papers[1] a method was described for finding the equation for calculating the viscosity from the time of discharge of an efflux viscosimeter. An equation was given for certain Saybolt Universal viscosimeters which happened to be available for test, but it was pointed out that this equation did not apply to instruments of standard dimensions, and in fact that standard dimensions had not been adopted.

On October 1, 1917, as a result of negotiations between Mr. George M. Saybolt and the Bureau of Standards, the dimensions and allowable variations shown in Table I were adopted as standard.

TABLE I.—DIMENSIONS OF THE STANDARD SAYBOLT UNIVERSAL VISCOSIMETER.

Dimension.	Minimum, cm.	Normal, cm.	Maximum, cm.
Inside diameter of outlet tube, d	0.1750	0.1765	0.1780
Length of outlet tube, l	1.215	1.225	1.235
Outer diameter of outlet tube, at lower end, d_2	0.28	0.30	0.32
Height of overflow rim above bottom of outlet tube, h_1	12.40	12.50	12.60
Diameter of container, D	2.955	2.975	2.995
Average head, h (calculated)	7.16	7.36	7.56

The average head is calculated from the equation

$$h = \frac{h_1 - h_2}{\log_e \left(\frac{h_1}{h_2}\right)} \quad \text{.................... (1)}$$

where h_1 and h_2 are the initial and final heads, respectively. This equation is the best available, although inaccurate except for very viscous oils. Since 60 cc. are run out of the viscosimeter during a test, it follows that

---

[1] *Proceedings*, Am. Soc. Test. Mats., Vol. XVII, Part II, p. 551 (1917); *Technologic Paper No. 100*, U. S. Bureau of Standards (1917).

$$\frac{\pi}{4} D^2 (h_1 - h_2) = 60 = Q \ldots\ldots\ldots\ldots\ldots \quad (2)$$

Equations 1 and 2 show that h is partly determined by D. Hence D is an essential dimension and must be specified as in Table I. Of less importance is the dimension d_2, although this also must be limited, as it determines the resistance due to surface tension.

As explained in the previous papers[1]

$$\frac{\text{Viscosity, in poises}}{\text{Density, g. per cc.}} = \frac{\mu}{\gamma} = At - \frac{B}{t} \ldots\ldots\ldots \quad (3)$$

where t = time of discharge in seconds;

$$A = \frac{\pi g d^4 h}{128\, Q\, (l + \lambda)}, \ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

$$B = \frac{Qm}{8\pi (l + \lambda)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

in which λ is the "Couette correction" which must be added to the measured length of tube to get the effective length, and m is the coefficient of the kinetic energy correction. All other quantities are known from Table I and Eq. 2, so that A and B of Eq. 3 may be calculated if λ and m are determined.

A and B may be determined, without the use of Eqs. 4 and 5, if suitable liquids are available of known kinematic voscosity (that is, known ratio of viscosity to density). Water is not a suitable liquid for short-tube viscosimeters because the flow is turbulent when water is used. The viscosity of glycerol solutions has not been determined with sufficient accuracy. Sucrose solutions are objectionable because the surface tension is much higher than that of the oils for which short-tube viscosimeters are generally employed. Thus solutions of ethyl alcohol and water are the best calibrating liquids which are readily available, although the attainable range of viscosity is somewhat limited.

---

[1] See preceding footnote; also E. C. Bingham and R. F. Jackson, *Scientific Paper No. 298*, U. S. Bureau of Standards, p. 65 (1917).

METHODS OF FINDING THE CONSTANTS *A* AND B.

Higgins' Method.—From Eq. 3 it is seen that if $\frac{\mu}{\gamma t}$ is plotted against $\frac{1}{t^2}$, the points will lie on a straight line if A and B are constant. The point where this line cuts the axis of ordinates gives the value of A, and the tangent of the angle between the line and the axis of abscissas gives the value of B. This has been called "Higgins' method."

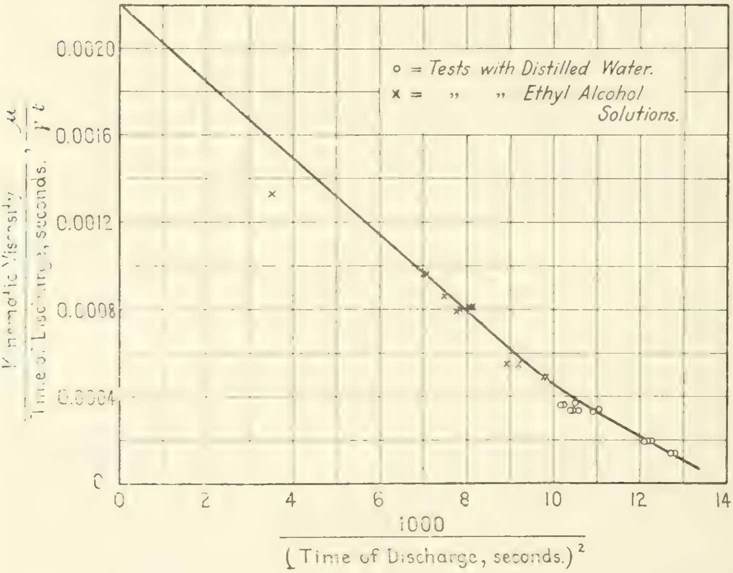


FIG. 1.—Calibration Curve of Standard Saybolt Universal Viscosimeter by a Modification of Higgins' Method.

Herschel's Method.—Let the mean velocity of flow be represented by $v = \frac{4Q}{\pi d^2 t}$ and let the expression $\frac{\gamma \pi g d^4 h t}{128\, Q l}$ be represented by μ'.

Then if $\frac{vd\gamma}{\mu}$ is plotted against $\frac{\mu'}{\mu}$

$$m = \frac{32\,l}{d \tan\theta} \quad \text{(6)}$$

$$\lambda = l\left(\frac{\mu'}{\mu} - 1\right) \quad \text{(7)}$$

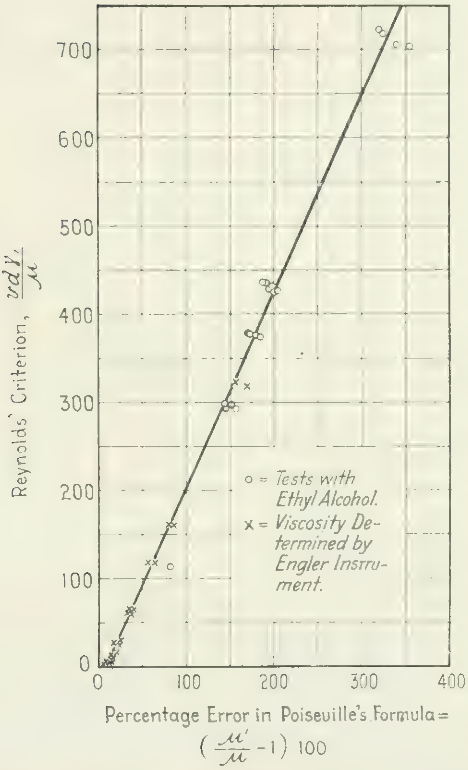


FIG. 2.—Calibration Curve of Standard Saybolt Universal Viscosimeter, by Herschel's Method.

where θ is the angle between the calibration curve and the axis of abscissas, and $\frac{\mu'}{\mu}$ in Eq. 7 is the value read at the point where the calibration curve, extended, intersects the axis of abscissas. This will be referred to as Herschel's method.

Modification of Higgins' Method.—When ethyl alcohol solutions are used for calibration purposes an excessive extrapolation is necessary. To avoid this difficulty use was made of the equation previously derived for Engler viscosimeter No. 2204 U:

$$\frac{\mu}{\gamma} = 0.00147\, t - \frac{3.74}{t} \qquad (8)$$

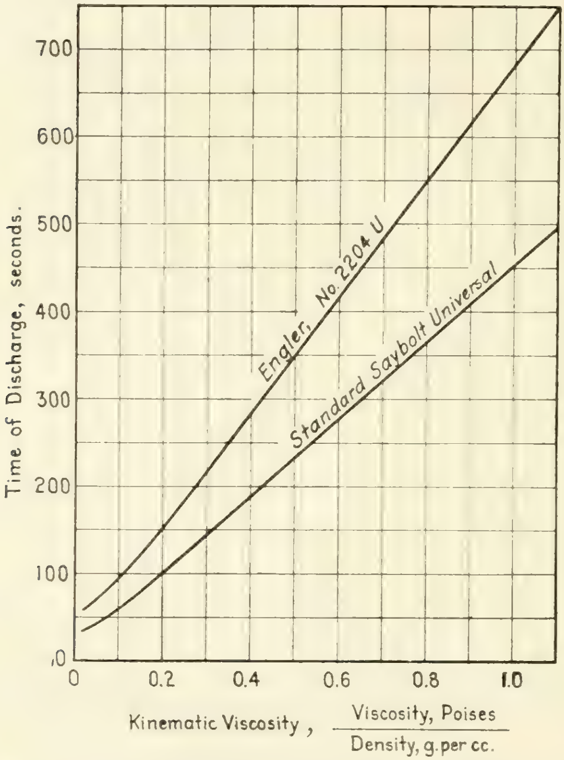


FIG. 3.—Plot of Equations for the Standard Saybolt Universal Viscosimeter and Engler Viscosimeter No. 2204 U.

If the kinetic energy correction is negligible, and Eq. 8 is combined with Eq. 3, then

$$A = \frac{0.00147 t_e}{t_s} \qquad (9)$$

t_e and t_s being the times of discharge for the Engler and Saybolt viscosimeters, respectively. It was found experimentally[1] that the time ratio, with very viscous oils, was 1.50, so that from Eq. 9, $A = 0.00220$. This fixes one end of the calibration curve in Fig. 1, and the other end is located from the tests with alcohol solutions. Then by Higgins' method, $B = 1.8$.

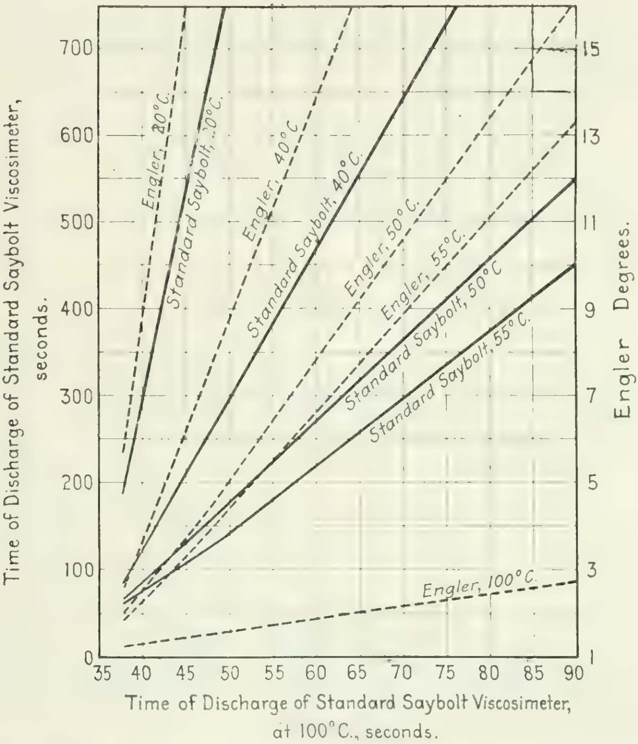


FIG. 4.—Diagram for the Intercomparison of Various Measures of Viscosity. This diagram shows approximately the change of viscosity with temperature which may be expected with a paraffin base oil, and should not be used except for rough estimates.

λ *and m by Herschel's Method.*—Fig. 2 shows the calibration curve as found by Herschel's method. By plotting tests at low velocities to a larger scale, it was found by extrapolation that the value of $\frac{\mu'}{\mu}$ when the velocity was zero would be 1.078, so that, by Eq. 7, $\lambda = 0.0956$ or $0.54\ d$. By using the average dimensions of the four instruments used in the tests (practically equal to the normal dimensions in Table I) in Eqs. 4 and 5, Eq. 3 may be written[1]

---

[1] A more detailed account of these experiments will appear in *Technologic Paper No. 112*, U. S. Bureau of Standards (1918).

$$\frac{\mu}{\gamma} = \frac{0.0029082}{1.226+\lambda}\,t - \frac{2.3873\,m}{(1.226+\lambda)\,t} \qquad \ldots\ldots\ldots\ldots (10)$$

Substituting the value of λ and neglecting the kinetic energy correction,

$$\frac{\mu}{\gamma} = 0.00220\,t = At \qquad \ldots\ldots\ldots\ldots\ldots\ldots (11)$$

Taking the value of $\tan\theta$ as 222.5 from Fig. 2, Eq. 6 gives a value of 0.998 for m, and then from Eq. 5, $B = 1.80$.

The complete equation for a Saybolt Universal viscosimeter of normal dimensions is therefore

$$\text{Kinematic viscosity} = \frac{\mu}{\gamma} = 0.00220\,t - \frac{1.80}{t} \qquad \ldots\ldots (12)$$

EQUATIONS FOR INSTRUMENTS WITH STANDARD BUT NOT NORMAL DIMENSIONS.

If the limiting, instead of the normal dimensions are used from Table I, Eq. 12 would become

$$\text{Kinematic viscosity} = 0.00211\,t - \frac{1.82}{t} \text{ (minimum)} \ldots (13)$$

$$\text{Kinematic viscosity} = 0.00230\,t - \frac{1.79}{t} \text{ (maximum)} \ldots (14)$$

Eq. 13 was calculated by selecting the dimensions which would tend to give a minimum time of discharge, while Eq. 14 was calculated from dimensions to give a maximum time. In practice there would be compensating deviations in the dimensions, so that the difference between times of discharge for different instruments would be less than indicated by Table II, calculated from Eqs. 12 to 14.

---

[1] These instruments are being remeasured by an improved method. The indications are that although slight corrections should be made on this and succeeding pages, they would be negligible in practical work.

APPLICATIONS OF THE NEW EQUATIONS.

It should be remembered that all previous work on the Saybolt Universal viscosimeter was with instruments not of standard dimensions, and consequently all formulas and diagrams are obsolete. Figs. 2, 3, 5 and 6 of the paper presented to the Society last year are here replaced by Figs. 1 to 4. It will be noted that in Fig. 3 Engler readings are expressed in seconds, and not in Engler degrees as in Fig. 4. While the latter method is the more common, it is objectionable because almost certain to be incorrectly referred to as relative or specific viscosity.[1] The temperatures employed in Fig. 4 are those recommended by Committee D-2 on Lubricants,[2] except 50° C., which is a temperature commonly employed with the Engler viscosimeter.

TABLE II.—TIMES OF DISCHARGE FOR STANDARD SAYBOLT UNIVERSAL VISCOSIMETERS.

Liquid.	Temperature.		Kinematic Viscosity.	Time, seconds.		
	Deg. Cent.	Deg. Fahr.		Minimum.	Normal.	Maximum.
30-per-cent ethyl alcohol	20	68	0.02841	34.7	35.7	37.0
	25	77	0.02292	33.4	34.2	35.4
50-per-cent ethyl alcohol	20	68	0.03144	35.5	36.6	37.9
	25	77	0.02636	34.2	35.2	36.3
A heavy oil	..	..	1.00	435	455	475

Table III has been calculated from Eqs. 8 and 12 of this paper, and Eq. 8 of the previous paper, namely,

$$\frac{\mu}{\gamma}=0.00213\,t-\frac{1.535}{t} \text{ (Saybolt Nos. 580 and 727)} \quad ..(15)$$

---

[1] For discussion of this point, see *Proceedings*, Am. Soc. Test. Mats., Vol. XVII, Part II, pp. 621 and 625 (1917).

[2] "Tentative Tests for Lubricants," *Proceedings*, Am. Soc. Test. Mats., Vol. XVII, Part I, p. 463 (1917).

It may be used for conversions between the Standard Universal viscosimeter and the Engler viscosimeter in place of tables given by Bacon and Hamor[1] and by Waidner.[2] It is impossible to say which equation or tables most nearly represent the average of all Saybolt Universal viscosimeters, not of standard dimensions, and now in use.

TABLE III.—CONVERSION FACTORS BETWEEN SAYBOLT UNIVERSAL VISCOSIMETERS AND ENGLER VISCOSIMETER No. 2204 U.

Engler No. 2204 U.		Saybolt Universal Viscosimeters.				Kinematic Viscosity, $\frac{\text{poises}}{\text{g. per cc.}}$
Time, sec.	Engler Degrees $= \frac{\text{Time}}{51.3}$[a]	Nos. 580 and 727		Standard		
		Time, sec.	Time Ratio.	Time, sec.	Time Ratio.	
56	1.09	30.8	1.82	32.4	1.73	0.0155
58	1.13	32.2	1.80	33.7	1.72	0.0208
60	1.17	33.6	1.79	35.1	1.71	0.0259
62	1.21	35.1	1.77	36.5	1.70	0.0308
64	1.25	36.5	1.75	37.8	1.69	0.0356
66	1.29	38.0	1.74	39.2	1.68	0.0403
68	1.33	39.4	1.73	40.6	1.68	0.0448
70	1.36	41.0	1.71	42.0	1.67	0.0495
75	1.46	44.6	1.68	45.5	1.65	0.0603
80	1.56	48.3	1.66	49.0	1.63	0.0709
85	1.66	52.0	1.63	52.4	1.62	0.0810
90	1.76	55.6	1.62	55.8	1.61	0.0905
95	1.85	59.3	1.60	59.4	1.60	0.1003
100	1.95	62.9	1.59	62.8	1.59	0.1095
110	2.15	70.4	1.56	69.8	1.58	0.1278
120	2.34	77.7	1.54	76.8	1.56	0.1453
130	2.54	84.9	1.53	83.6	1.56	0.1624
140	2.73	92.0	1.52	90.6	1.55	0.1793
150	2.93	99.1	1.51	97.4	1.54	0.1956
160	3.12	106.4	1.50	104.4	1.53	0.2121
180	3.51	120.5	1.49	117.7	1.53	0.2437
200	3.90	134.6	1.49	131.5	1.52	0.2753
225	4.39	152.1	1.48	148.3	1.52	0.3140
250	4.88	169.9	1.47	165.3	1.51	0.3523
275	5.36	187.1	1.47	182.0	1.51	0.3904
300	5.85	204.3	1.47	199.0	1.51	0.4282
325	6.34	221.9	1.46	215.6	1.51	0.4660
350	6.82	239.1	1.46	232.9	1.50	0.5038
375	7.31	256.7	1.46	249.2	1.50	0.5413
400	7.80	273.9	1.46	266.1	1.50	0.5784
500	9.75	343.1	1.46	333.0	1.50	0.7271
600	11.70	412.1	1.46	400.0	1.50	0.8753
800	15.59	550.8	1.45[b]	533.3	1.50[b]	1.1707

[a] See *Technologic Paper No. 100*, U. S. Bureau of Standards, p. 23.
[b] This value holds good for all higher viscosities.

---

[1] R. F. Bacon and W. A. Hamor, *The American Petroleum Industry*, Vol. I, p. 111 (1916).

[2] C. W. Waidner, *Proceedings*, Am. Soc. Test. Mats., Vol. XV, Part I, p. 284 (1915).

THE VARIABLE-PRESSURE METHOD FOR THE MEASUREMENT OF VISCOSITY.

By E. C. Bingham.

SUMMARY.

This paper sums up the difficulties encountered in measuring viscosities by the pendulum method and by the capillary-tube method, and points out the very marked advantages to be derived by modifying the present capillary tube viscosimeters so as to use variable pressures.

THE VARIABLE-PRESSURE METHOD FOR THE MEASUREMENT OF VISCOSITY.

By E. C. Bingham.

Viscosity is invariably measured by setting up a condition of shear within a fluid. This may be be brought about by the movement of one surface in respect to some other surface, the space between being filled with the viscous medium; or the shear may be produced by some force such as gravitation, hydrostatic pressure, etc., without the movement of the walls of the containing vessel. A study of the multitude of devices for measuring viscosity reveals the fact that they may be classified under these two heads. The pendulum method of Coulomb[1] is a type of the first class, as the capillary-tube method of Poiseuille[2] is a type of the second class.

Difficulties in the Use of the Pendulum Method.

Experiment has shown that the first class of methods is open to three main objections:

1. If the space between the shearing surfaces is large the rate of shear must be very small, otherwise the linear character of the flow is lost and turbulent flow ensues, which is governed by quite different laws from those governing viscous flow.
2. On the other hand, if the shearing surfaces are close together, the resistance to flow being dependent upon their distance apart, it involves serious experimental difficulties to maintain this distance uniformly and to measure it accurately.
3. The constancy of the solid material which is being subjected to torsional movement, as the wire supporting the pendulum, is difficult to maintain.

Difficulties in the Use of the Capillary Tube Method.

The above objections do not apply to the capillary tube method, where the fluid is forced to move through a narrow channel by means of gravity or some other suitable force. This method depends upon the fact, now quite well established,[1] that in viscous flow the liquid in contact with the walls of the channel is at rest.

---

[1] Mem. de l'Instit. nat. des Scienc. et Arts Scienc. Math. et Phys., Vol. 3, p. 246 (1801).

[2] Mem. present. par divers Savants a l'Acad. Roy. des Scienc. de l'Instit. de France, Vol. 9, p. 433 (1846).

The formula for the viscous flow of a liquid through a capillary of uniform circular cross-section[2] is now generally accepted to be

$$\eta = \frac{\pi g r^4 p t}{8 v (l+\lambda)} - \frac{m n \rho v}{8 \pi t (l+\lambda)} \quad \dots\dots\dots\dots\dots (1)$$

in which η = the viscosity in absolute c. g. s. units;
π = 3.1416;
g = the gravitation constant of the locality;
r = the radius of the capillary in centimeters;
p = the pressure in grams per square centimeter used up in producing the flow;
t = the time in seconds;
v = the volume in cubic centimeters;
l = the length of the capillary in centimeters;
λ = the correction to the length of the capillary for the so-called "end effect", which is negligible for a long capillary;
m = a coefficient, probably 1.12;
n = the number of capillaries in use in the instrument; and
ρ = the density of the liquid.

But there has been slowly developing a realization that various precautions must be taken if thoroughly satisfactory results are to be obtained even with the capillary tube method.

1. The formula is valid only when the velocity of flow remains below a certain well-marked limit.[3] Above this limit the flow ceases to be linear and becomes turbulent.

2. The value of the coefficient[4] m is perhaps dependent

---

[1] Whetham, Philosophical Magazine, *Proceedings* Roy. Soc., Vol. 48, p. 225 (1890).

[2] Zeitschr. für physik. Chem., Vol. 80, p. 670 (1912).

[3] Osborne Reynolds, *Philosophical Transactions*, Vol. 174, p. 935 (1883); Vol. 177A, p. 157 (1886).

[4] Zeitschr. für physik. Chem., Vol. 80, p. 670 (1912).

upon the character of the end[1] of the capillary, hence its value may be open to some doubt unless determined by experiment for the given conditions under which it is proposed to measure the flow.

Fortunately the term of Eq. 1, in which the coefficient m appears, represents merely the kinetic energy of the liquid as it leaves the capillary, and this may theoretically, at least, be made as small as desired by adjusting the conditions of flow.

3. The effect of the ends of the capillary,[2] expressed by adding a distance λ to the length of the capillary, is quite distinct in theory from the kinetic energy correction. As the liquid enters the capillary, there is produced an alteration in the stream lines just inside the entrance to the capillary. There is a certain amount of shear taking place outside the entrance to the capillary. Here again the value of the correction may be dependent upon the shape of the end of the capillary. In view of the uncertainty with regard to the exact value to be taken for λ it is certainly desirable to employ a long capillary in order that the uncertainty arising from this source may be made as nearly negligible as practicable.

It so happens that the instruments most used at the present time in commercial testing were devised at a time when the most favorable conditions of flow were imperfectly understood, and it is therefore not surprising that the difficulties mentioned above are not met to the best advantage. For example, in the Engler viscosimeter[3] the calibration of the instrument is made with water at 20° C. The velocity of flow is nearly the critical velocity at which turbulent flow begins. Of the total energy expended in the flow over 90 per cent[4] is used in merely imparting kinetic energy to the liquid, leaving less than 10 per cent to be used up in overcoming viscous resistance. Having this kinetic energy correction of over 90 per cent puts the method of measurement at a decided disadvantage.

Since the capillary is very short—2.0 cm.—the end correction may come in for consideration.

---

[1] Bingham, Schlesinger, and Coleman, *Journal*, Am. Chem. Soc., Vol. 38, p. 27 (1916).

[2] Thorpe and Rodger, *Philosophical Transactions*, Vol. 185A, p. 437 (1894).

[3] Tabellen zum Englerschen Viskosimeter, by Ubbelohde.

[4] *Bulletin No. 298*, U. S. Bureau of Standards, p. 60 (1917).

4. But there are other criticisms of technical instruments of the Engler type. The flow is produced by the head of liquid in the viscosimeter, which is objectionable. Since oils vary widely in viscosity, it would be highly advantageous to use higher pressures in measuring the viscosities of the more viscous oils, in order to prevent a large waste of time in measuring the time of outflow; but the density of the more viscous oils is not appreciably higher than that of the more fluid oils or that of water, used in the calibration.

5. It is often assumed that the times of flow of two substances are proportional to their viscosities. That this is not strictly true is evident at once from Eq. 1. Moreover, two substances having equal times of flow, but unequal densities, would not have equal viscosities. Hence it is not satisfactory from the theoretical point of view to follow current practice and use times of flow in place of true viscosities. It is urged that the theoretical and the practical points of view must eventually agree since the property of viscosity can only find its widest application by the extensive use of the purely theoretical considerations. Viscosities should be recorded in absolute units, but to obtain absolute viscosities using instruments of the Engler type, it is necessary to make a supplementary determination of the density of the liquid and to the same degree of accuracy to which the viscosity is desired.

6. In the type of instrument under discussion, the liquid flows out into the air. This is unfortunate since with some oils the flow takes place in a steady stream, while with others the flow is in drops. The surface tension as the drop begins to form at the end of the capillary tends strongly to repress the flow.[1] This action is not taken into consideration at all in the calculation, probably because the effect is masked by other sources of error of a more serious character.

7. One of the most serious criticisms against the instruments in common use is the lack of proper temperature control.

(*a*) The capillary is not completely immersed in the bath so that its temperature is not necessarily uniform throughout.

(*b*) The bath is small and inadequately stirred so that it is difficult to obtain a definite temperature and maintain it uniformly for a considerable period of time.

---

[1] Ronceray, Annales de chim. et de phys., Vol 22, p. 107 (1911).

(*c*) The volume of flow of the 200 cc. usually taken is quite large, so that the liquid comes to the temperature of the bath comparatively slowly. This condition is aggravated by the fact that in viscous oils both conduction and convection of heat is greatly reduced. Furthermore the oil to be measured is not stirred and motion in the oil about to be measured is regarded as disadvantageous since it may start vortex motion of the liquid at the entrance of the capillary.

(*d*) Still more serious, however, is the fact that as soon as the warm oil has flowed out into the receiving flask, it becomes chilled, so that the bath must be warmed up above the required temperature in order to bring the oil to temperature before a duplicate determination can be made. The operator now faces a dilemma, for although the liquid to be measured is at the correct temperature, the temperature of the bath is somewhat higher. He may either take the time necessary to bring the temperature of the bath back to the proper value, which is laborious, or he may begin the determination somewhat before the liquid to be measured has come to temperature, in the hope that the liquid will be as much above the temperature at the end of the run as it was below at the beginning; but there is little assurance that such a hope will be justified. Finally, the operator may have a supplementary bath in which to bring the temperature of the liquid up to the proper value, before it is introduced into the viscosimeter. It is hardly to be expected, however, that one person can regulate two baths by hand simultaneously. The result is that the measurements are difficult to make and the results are disappointing because they often fail to check when the conditions are apparently the same.

(*e*) To secure results which are somewhat more dependable experimenters sometimes take the average of ten readings for each value desired. This is open to the objection of being very time-consuming if not quite impracticable for the very viscous oils. The procedure is quite unjustifiable in view of the accuracy obtainable.

8. After all, the most serious objection to this type of instrument is that the pressure at the disposal of the operator

is determined by the specific gravity of the liquid, which varies within very narrow limits only, whereas the viscosity varies between the widest limits -from zero to infinity in theory, and in ordinary oil testing from the viscosity of water at 20° C. of 0.010 to the viscosity of castor oil at 20° C. of 10.0.[1] If therefore water requires 51 seconds to transpire, the same volume of castor oil will require several hours. This makes the operation tedious. If however the operator chooses to make the efflux volume less in order to reduce the amount of time consumed, he encounters theoretical difficulty in interpreting his results.

9. Finally, there is an objection in principle to the methods which permit the liquid to be exposed to the air, on account of the possibility of evaporation of volatile constituents, of absorption of water from the air, or of contamination with dust.

THE VARIABLE-PRESSURE METHOD.

The present paper is an inquiry as to whether the above difficulties in commercial testing may not be overcome, as they have been in purely scientific work, by the use of an instrument in which the flow is not dependent upon a hydrostatic head of the liquid but may be varied at will to suit the requirements of the operator.

The essential part of the apparatus is shown in Fig. 1. Two similar bulbs *C* and *K* are connected by the long straight capillary *EF*. The liquid is introduced at *M* and forced through the instrument until the liquid runs over into the trap *A* and the other meniscus stands at *H*. This so-called "working volume" is adjusted each time that liquid is introduced or the temperature changed.

To make a viscosity measurement, pressure from a reservoir connected with a suitable manometer is admitted to the left limb and the right limb is connected to atmospheric pressure. The time is taken as the meniscus passes the marks *B* and *D*. Knowing the time, the pressure, and the temperature the measurement is complete, and the liquid is in position for an immediate determination in the opposite direction.

---

[1] Kahlbaum and Räber, Abhand. der Kaiserl. Leop. Carol. Deutsch Akad. der Naturforsch., Nova Acta, Vol. 84, p. 203 (1905).

The advantages of the apparatus are as follows:

1. The viscosimeter may be immersed in a large bath so as to obtain complete temperature control.

2. The pressure may be varied at will so that the kinetic energy correction may be made as small as desired even for very fluid substances. With very viscous liquids, on the other hand, the time of flow may be reduced to a reasonable value by merely increasing the pressure.

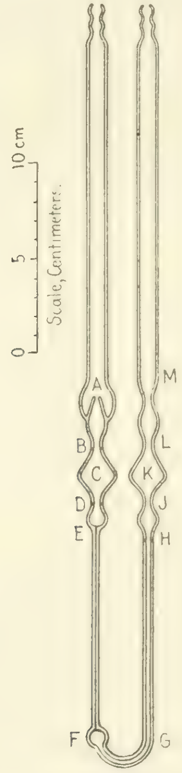


FIG. 1.—The Viscosimeter.

3. The apparatus is ready for a duplicate determination in the opposite direction as soon as the first determination is completed, hence there is a large saving of time.

4. The volume of flow is small, being less than 10 cc. This

produces an economy of material, reduces the time of flow, and promotes a rapid attainment of thermal equilibrium between the liquid in the viscosimeter and the bath. This may be further hastened, if desired, by forcing the liquid through the capillary, which stirs the liquid efficiently.

5. The liquid in the instrument is not exposed to dust or other contamination, and in addition evaporation is prevented.

6. The instrument, when mounted in its frame, may be easily cleaned out by means of the ordinary cleaning and drying fluids, such as fuming nitric acid, water, alcohol, and ether. The liquids may be readily forced through the instrument by means of pressure or drawn through by means of suction. In keeping the instrument clean it is a distinct advantage that the instrument is transparent and not corroded by acids.

7. The capillary being long and the velocity of flow low, the viscosity formula given in Eq. 1 applies exactly, so that the results obtained are not only reproducible but they are expressed in absolute units. The formula reduces to the very simple expression

$$\eta = C p t - \frac{C' \rho}{t} \quad \text{. . . . .} \quad (2)$$

in which C and C' are constants of the apparatus. The term $C'\rho/t$ is the kinetic energy correction, which may be made as small as desired but should always be kept low and not exceed five per cent of the term $C\,p\,t$.

8. If the bulbs C and K in the figure are at the same height and similar in shape and of equal capacity, the pressure will not be appreciably dependent upon the density of the liquid. It is not practicable for the glass-blower to attain this result exactly, so that there may be a small hydrostatic head[1] amounting to one or two millimeters of liquid. The density is also required in calculating the kinetic energy correction, but since these corrections are small, the density need not be known accurately in order to secure accurate determinations of the viscosity.

---

[1] For method of calculating the hydrostatic head see *Bulletin No. 298*, U. S. Bureau of Standards, p. 65 *et seq.* (1917).

9. The "constants" of Eq. 2 are readily obtained. The absolute viscosity of water at 20° C. is known to be 0.01005 with a fair degree of certainty.[1] If we assume this value as correct it is unnecessary to measure accurately the dimensions of the viscosimeter. The method of calibrating the instrument is described in Bulletin No. 298 of the U. S. Bureau of Standards.

10. The possibility of determining the viscosity of a given liquid, for example, water at 20° C., at a variety of pressures gives a valuable flexibility to the apparatus, whereby it is practicable to ascertain whether the values of the "constants" are what the name implies.

11. Since the capillary opens at either end into a mass of liquid under all conditions, and the apparatus is symmetrical in shape, there is no appreciable correction for surface tension.[2]

12. The shape of the instrument is such that errors due to faulty drainage are reduced to a minimum, and they are made evident at once by lack of constancy in the duplicate determinations in opposite directions, since in the original determination the volume of flow is the volume of *delivery of* the bulb *C*, while the duplicate determination is made with the volume to fill the same bulb.

13. The employment of a trap makes possible the adjustment of the working volume with ease and precision.

14. Since it is not necessary to arbitrarily fix upon the dimensions of the apparatus within narrow limits, the apparatus may be constructed without great cost and the ordinary plumber can connect the pressure-reservoir, manometer, etc., to the viscosimeter. The glass instrument is already being supplied to the trade by Eimer & Amend. It would probably be feasible for them to supply the complete apparatus in a self-contained form, with bath, frame for the viscosimeter, reservoirs, air-pump, valves, manometer, and thermometers if the conditions demand it.

15. Most important of all is the fact that the viscosimeters now in use give values which are often inaccurate to the extent of several per cent, whereas with an instrument of the type herein described it is quite possible to make determinations

---

[1] See *Bulletin No. 298*, U. S. Bureau of Standards, p. 74 (1917).

[2] Bingham, Schlesingerand Coleman, *Journal*, Am. Chem. Soc., Vol. 38, p. 40 (1916).

which are accurate to a tenth of one per cent[1] with no increase in the expenditure of time, with only a small outlay in money, and with no particular manipulative skill. The technic is not at all difficult when once mastered, the calibration of the instrument is probably not more difficult than the calibration of any instrument of precision, and when once calibrated the results are calculated quickly and easily.

There are some who object to the use of absolute viscosities since they are usually inconveniently small decimal fractions. This difficulty is best avoided by expressing the results as fluidities, which are more comparable with each other than are the viscosities, thus securing a very great advantage. The difficulty may also be overcome by expressing the results in centipoises.[2]

---

[1] Kendall and Munroe, *Journal*, Am. Chem. Soc., Vol. 39, p. 1794 (1917); White, *Journal of Industrial and Engineering Chemistry*, Vol. 4, p. 267 (1912); Bingham, Schlesinger and Coleman, *Journal*, Am. Chem. Soc., Vol. 38, p. 33 *et seq.* (1916); Bingham and Jackson, *Bulletin No. 298*, U. S. Bureau of Standards, p. 70 (1917).

[2] Bingham and Jackson, *Bulletin No. 298*, U. S. Bureau of Standards, p. 72 (1917).

DISCUSSION.

Mr. Herschel. MR. WINSLOW H. HERSCHEL.—The greatest uncertainty in regard to viscosity of oils is what viscosity will give the best results in a given machine. The error in using a short-tube instead of a long-tube viscosimeter is small in comparison.

I am often told that the accuracy that is obtained with the Saybolt viscosimeter is not great enough. It all depends, of course, on what use is made of viscosity, and it should be borne in mind that there are other liquids in the world besides oils; there are other materials of which we have to find viscosity; there is ink, various liquids used in the airplane, and a great variety of substances, and the use of viscosimeters is greatly increasing. Therefore I do not think we ought to confine ourselves to any one type of viscosimeter simply because it is of an accuracy suitable for a particular kind of liquid or a particular kind of work.

Now, as far as refineries are concerned, it seems to me probable that, for a great many cases, the short-tube viscosimeter is plenty accurate enough. I would go further; I would say that undoubtedly, in a great many cases, a tin can with a hole in it is plenty accurate enough for the purposes for which a Saybolt viscosimeter is used; but, on the other hand, there are a great many cases where the Saybolt viscosimeter is not accurate enough in dealing with other liquids than oils, and where the viscosities should be determined with as great accuracy as possible. For cases like that, this instrument described by Mr. Bingham becomes of exceeding interest, and I am most heartily in agreement with him that some such instrument as that should be used.

I think we should make a distinction between accuracy and reproducibility of results. When I speak of accuracy I have in mind a different thing from what Mr. Bingham speaks of; his idea seems to be reproducibility, whereas by accuracy I mean approach to the truth.

Mr. Herschel.

In regard to the variable-pressure method of measuring viscosity, I believe it would be preferable to omit the letter *n* in the last term of Eq. 1. For the purpose of determining the value of *m* it is convenient to use several tubes so as to magnify the effect of the kinetic energy correction, but where the object of the experiment is to measure viscosity there should be only one tube so that this correction should be as small as possible.

The doubtful quantities in Eq. 1 are λ and m. Knibbs[1] found from a study of Poiseuille's experiments an average value of 1.14 for m. Hosking[2] found a value of 1.158 from his own tests. For any given series of tests, the constancy of the viscosity as calculated from Eq. 1 is an indication of the correctness of the assumed value of m. Taking m equal to 1.12, Bingham and White[3] found that a variation of the number of tubes from one to six caused a variation of 0.4 per cent in the calculated viscosity. I find that m could be increased to 1.20 without causing any greater variation. Although there is thus considerable uncertainty in regard to the value of m, if, as recommended by Mr. Bingham, the last term of Eq. 2 is not over five per cent of the term Cpt, this uncertainty in the value of C' will cause an error of less than 0.1 per cent in the calculated viscosity.

The uncertainty in regard to the value of λ is more serious. Higgins[4] concludes on theoretical grounds that λ is equal to 82 per cent of the diameter for submerged discharge. Hosking found the same value experimentally. Kahlbaum and Räber (referred to in Mr. Bingham's paper) found that λ was equal to three diameters, as previously found by Couette. This also agrees fairly well with the results I found graphically from Poiseuille's tests.[5]

The greatest possibility of error is thus seen to be in the assumption in regard to the value of λ. If the true value may be either zero or three diameters, and 1.5 diameters is assumed,

---

[1] G. H. Knibbs, *Journal* and *Proceedings*, Royal Society, New South Wales, Vol. 29, pp. 97–103 (1895).

[2] R. Hosking, *Philosophical Magazine*, Vol. 18, p. 260 (1909).

[3] E. C. Bingham and G. F. White, *Zeit. f. physikalische Chemie*, Vol. 80, p. 670 (1912).

[4] W. F. Higgins, "Collected Researches," National Physical Laboratory, Vol. II, p. 10 (1914).

[5] Winslow H. Herschel, *Technologic Paper No. 100*, U. S. Bureau of Standards, p. 30 (1917).

Mr. Herschel. a tube 1500 diameters in length would be necessary in order to insure an accuracy of 0.1 per cent.

Mr. Bingham. MR. E. C. BINGHAM.—I agree with Mr. Herschel as to the desirability of evaluating with the utmost care each factor which goes to make up the value of the constant C, whenever the measurements are absolute. But we are not interested in the point which he raises in purely relative measurements, which are used for all technical purposes. We should adopt the viscosity of water at 20° C. (1.005 poises) as standard, because water has been accurately measured by a considerable number of investigators, working under conditions such that the factor discussed by Mr. Herschel is negligible. Having adopted this viscosity as standard, the exact value of λ in Eq. 1 becomes of no interest, for the reason that the constant C of the instrument is obtained by simply measuring the rate of flow of water at 20° C. without any reference to λ. The other constant of the instrument C' is obtained by a rough measurement of the dimensions of the instrument.

Since n in Eq. 1 is usually unity, it is perfectly justifiable to omit it from the formula as Mr. Herschel suggests.

INTERNAL-COMBUSTION ENGINE: LUBRICATION AND LUBRICANTS.

By P. H. Conradson.

SUMMARY.

The essential factors to be considered in the selection of a proper lubricant for internal-combustion engines are the type and condition of the machine, the method of applying the lubricant, and the construction of the lubricating system, as well as climatic conditions. The lubricant should have sufficient body to produce a proper film between the working surfaces both when the engine is first started and after it becomes heated, so as to act as an efficient seal to prevent gaseous vapors leaking past the piston rings and condensing in the oil.

Finally, the oil must be of the highest purity, properly refined, with all objectionable impurities removed.

INTERNAL-COMBUSTION ENGINE: LUBRICATION AND LUBRICANTS.

By P. H. Conradson.

While railroad engines, ship engines and similar traveling machines, as well as stationary steam engines of all kinds and sizes, have been in use so long that the problems connected with the proper lubrication of their various parts have been solved, the rise of the internal-combustion engine, particularly as applied to airplanes, automobiles, trucks, tractors, motor-boats, etc., has introduced many new factors in the selection of proper lubricants to meet the requirements. Even before the world war began there was a growing appreciation of the importance of giving intelligent study to the selection of lubricants for internal-combustion engines, and as the war continues we are faced more and more with greater lubrication problems, especially in connection with the many new designs, service conditions and requirements.

The internal-combustion engine is the engine of the day—not only on the highway, but on the water, under the water, in the air and under the ground. Summarizing briefly, we may include under this head engines for the various types of airplanes and automobiles, gas engines, Diesel engines, and engines for tractors of all kinds, agricultural as well as military, including the great tanks in use at the battle fronts, thereby transferring this perfected form of power from the realm of imagination into useful existence.

There are two principles involved in this form of power: internal explosion and internal combustion. The Diesel or similar oil-burning engines employ only the internal-combustion principle. Here the liquid fuel, finely atomized by air, is injected under high pressure into the combustion chambers, which contain air compressed to a sufficiently high degree to obtain a temperature far above the igniting point of the fuel, where complete and gradual combustion follows.

Without doubt internal-combustion engines are the most difficult to lubricate, and probably require more study than any other mechanism, due to the exposure of the oil film to extremely high temperatures, as well as to severe service conditions. Many factors enter into the problem, among which might be named: (1) Method of cooling system or operating temperature; (2) clearance space between working parts; (3) rubbing speed of surface in contact; (4) load carried by the engine; (5)working at full power for long periods; (6) varying climatic conditions; (7) oiling system.

SYSTEMS OF LUBRICATION.

The systems of lubrication commonly in use on the various engines are: Full splash, circulating pump with splash, pump over and splash, force feed and splash, pump over, force feed, full force feed, slide-valve engine and oil fed with fuel. These may be grouped into "circulating systems" and "all-loss systems." The various types are too well known to warrant further explanation. The splash system of lubrication is a "makeshift" in anything but the smaller motors, in which it may be used quite effectively. The lubrication of large cylinders is usually done by timing the delivery of the lubricant under pressure so that it enters between the rings of the piston.

SELECTION OF THE OIL.

The main considerations in the selection of oil for the various classes of service are not very well understood. Too much weight is given to vague inferences as to the relative value of viscosity and flash point alone, without taking into consideration many other important factors; and while it is true that some few engine manufacturers have conducted exhaustive investigations to determine just what particular grade of oil should be used for their engine, the greater part of the work of developing suitable lubricants for the various combustion engines has been done by the refiners and dealers of oil, who are thus rendering excellent service in this field both to the user and the manufacturer.

Viscosity.—While the determination of viscosity—that is, body or consistency at a given temperature –is one of the vital tests usually applied to lubricating oil for internal-combustion engines, it is of importance only when the user of the oil is thoroughly familiar with the characteristics of the different crude oils of which it is made, and is sure that the mechanical condition calls for the use of an oil having the stated viscosity. Two oils of the same viscosity, made from different crudes, may behave quite differently under identical working conditions.

The determination of viscosity of an oil, to be of the greatest value, should be made not only at the lower temperatures, but also as near its using temperature as consistent. On the one hand, an oil of low viscosity might be preferable, since it absorbs less power than a thicker oil in the separation of metallic surfaces moving at a high velocity over each other; in other words, high viscosity means a high internal friction. On the other hand, if the oil is too thin it is more easily displaced from between the bearing sufaces, and a heavier oil might then be preferable, as the engine will be more flexible at low speed, owing to better seal and less leakage. Therefore, due consideration must be given to the influence of temperature on the viscosity, and to the necessity of selecting just the proper grade for the service required.

Owing to the comparatively high temperature under service conditions, there generally is no trouble from the oil being too thick when once in use. However, an oil must possess a degree of fluidity at ordinary temperatures—which are influenced by climatic conditions—suited to the method of supplying the oil to the working parts, so as to obtain proper lubrication at the start. A lubricating system with exposed pipes, especially a force feed system, should have a lower "cold-test" oil to meet these conditions; while in a system where the oil is carried in a pump integral with the engine crank case, and where the supply pipes are not exposed, all parts of the system quickly become sufficiently heated to promote a positive circulation and an oil with a higher "cold test" may be used with good results.

Flash Point.—The flash point of an oil is of no particular value after the oil has once entered the explosion chamber, where the temperature is considerably higher than that at flash point. Nevertheless, it is important to use an oil of sufficiently high flash point for reasons of economy if for no other, to resist the vaporization which takes place when the oil comes in contact with the highly heated surface of the piston head, and other parts below the piston. In considering this it is well to remember that with many oils there is very little connection between the evaporation (heat) loss and the flash point. Investigation has shown that while two oils may have the same flash points, the percentages of evaporation loss at a given temperature may be quite different. Generally speaking, however, the evaporation loss is greater in oils having a low flash point.

Obviously that oil which, when subjected to an evaporation test at a certain temperature, loses the least, and leaves a residue which has been broken up or altered in character as little as possible by the heat treatment, is the most desirable for lubrication of internal-combustion engines. Therefore, the evaporation and oxidation tests offer a very promising means of examining the oil and noting the changes that develop in different oils under similar conditions of treatment.

Oil consists principally or entirely of chemical compounds of carbon and hydrogen (hydrocarbons). At high temperatures these hydrocarbons decompose, forming volatile combustible gases and heavy hydrocarbons, or carbonaceous matter, and free carbon. This breaking up may be due to a certain extent to improper methods of refining or to the nature of the crude oil. Only the most highly refined and filtered oils should be recommended to meet these conditions.

Carbon Residue.—Much has been written about the carbon residue of the oils for this class of service. The carbon in all oils can be fixed by driving off the oil vapors (without addition of air), leaving a layer of carbon deposit which is called carbon residue. The condition of the carbon formation in the cylinder is somewhat different from that found in the carbon residue test, due to the fact that in the cylinder the oil is spread out in a thin film on hot metal surfaces, and exposed to the burning gases of the explosion, which may carry widely varying amounts of oxygen to combine with the oil. Also, the amount of carbon deposited in the cylinders is governed by the amount of oil reaching the explosion chamber, and may depend to a great extent upon the mechanical fit of the pistons, piston rings and cylinders. It is expected that some oil will find its way into the combustion space, but it is assumed that it will be burned up without depositing an excessive amount of carbon on the cylinder walls and pistons.

One of the most injurious effects of improper lubrication is the formation of this carbon deposit around and under the piston rings. Such a deposit soon renders the spring rings inoperative; they become partially fastened in their grooves, and in this condition form one of the most prolific causes of cut and scored cylinders, and broken piston rings. One of the causes of this trouble may be the use of too much oil. From the result of much investigation along this line it has been conclusively demonstrated that an oil with the lowest carbon residue, other things being equal, will leave behind the lowest carbon deposit in the explosion chamber.

In connection with the physical characteristics of the carbon deposit it is of importance to select a lubricant which leaves a loose and flaky or soft carbon deposit, easily removed, rather than one leaving a dense, hard deposit difficult to remove.

Specific Gravity.—The specific gravity of the oil need not be taken into serious consideration, unless there should be some relation between the specific gravity and certain chemical characteristics of the oil which go to determine its lubricating value. The specific gravity will in no way determine whether the oil will stand up under service conditions.

CONCLUSIONS.

The selection of the proper grade of oil for each class of service therefore depends upon a number of factors, such as the type and condition of the machine, the lubricating system and the method of applying the lubricant, and the method of cooling, as well as climatic conditions.

One of the essential points in the selection of lubricants is that they should have sufficient body to not only make proper seal at the start when the clearance between the piston rings and cylinders may be great, but also when the engine becomes highly heated, to prevent the gaseous vapors from leaking past the piston rings and condensing in the oil in the system, thereby reducing the efficiency of the lubricant.

Acknowledgment.—The author is pleased to acknowledge the valuable aid and suggestions in preparing this paper which were given by Mr. Charles B. Karns, Assistant Chemist, Galena Signal Oil Company.

THE SAMPLING OF DEPOSITS OF ROAD STONE AND GRAVEL IN THE FIELD.

By L. Reinecke and K. A. Clark.

SUMMARY.

The engineer is dependent very largely upon the results of laboratory tests for a knowledge of the roadmaking values of natural deposits of stone and gravel. The tests are made upon small samples taken from much larger deposits and the value of the laboratory tests, therefore, depends directly upon the degree to which the samples represent the deposits.

A series of studies have been begun upon variations in the roadmaking qualities of deposits of bedrock, boulder aggregates and gravel. The field is very wide and this paper covers only a small part of it.

Scheme of Experimentation.

Bedrock.—As a preliminary to the study of the variations in the rock deposits, tests were made to determine variations that might arise through laboratory manipulation, the operation of sampling, and the difference between the results of tests upon samples of stone taken from the quarry face and samples of crushed stone from the same quarry.

The variations in durability of the stone occurring in limestone or dolomite sedimentary formations were studied by means of abrasion and toughness tests on samples from various parts of the formations.

The variations in durability of the stone occurring in a series of large diabase (igneous) dikes of the same age, structure, and composition, were compared in the same way.

Boulder Aggregates or Field Stone.—Studies were made to determine the best methods of arriving at the average durability and the variation in quality of the large deposits of boulder aggregates piled in fences and heaps through Canada and the northern part of the United States. The rock varieties in the aggregates were classed into three or four types of about the same average durability. These were sampled separately and the relation of their percentages of wear to the percentages of wear of various combinations of them were found by experiment.

Gravel.—The deviation in granulometric analyses as determined by standard laboratory methods of two portions taken from the same laboratory sample, and the deviations between analyses made in the laboratory and the field were determined.

Variations in texture over a deposit of sand and gravel covering 800 acres were determined by combined laboratory and field tests.

The conclusions are given in detail in the paper.

THE SAMPLING OF DEPOSITS OF ROAD STONE AND GRAVEL IN THE FIELD.

By L. Reinecke and K. A. Clark.[1]

This paper is a record of the beginning of a series of studies undertaken by the Department of Mines of Canada upon the variations in quality of deposits of road stone and gravel as they exist in the field. They were undertaken with the object of determining the methods that should be used in sampling the stone for laboratory tests and more particularly the location and number of samples that should be taken from any given deposit in order that a comparatively close estimate of its average value might be arrived at.

The natural non-bituminous deposits the engineer is called upon to use for road work occur either as bedrock, boulder aggregates or gravel. The bedrock can be divided further into igneous, sedimentary and metamorphic rock, each class varying widely from the others in composition and texture.

Studies of the variation in quality of the material making up a typical limestone or dolomite sedimentary formation were made and some data bearing upon the variation found in igneous masses were obtained. A new method is proposed for sampling boulder aggregates in the field and the relation between variations in boulder composition and variations in the durability of the boulder aggregate is demonstrated. In the study of gravel deposits attention is called to the possible variations in the results of mechanical analyses arising from laboratory manipulation and the variation in the grading of a large gravel deposit of the "outwash glacial" type is described.

BEDROCK.

Scheme of Experimentation.—As a preliminary to the study of the variation in the rock deposits it became necessary to determine the amount of variation in the results of tests that might arise from causes other than the quality of the stone itself.

---

[1] The experiments on the sedimentary formations and on the boulder aggregates were developed and carried out by Mr. K. A. Clark.

I. With this object in view experiments were conducted to determine:

(*a*) The probable variation in the results of abrasion tests due to laboratory manipulation.

(*b*) The probable variation in the results of abrasion tests due to the operation of sampling.

(*c*) The probable variation in the results of abrasion tests on samples collected from the rock in place in a quarry and from the material obtained as a crushed product from the same quarry.

The abrasion test was used in this and other studies because it gives the most valuable data as to the strength and durability of a stone and because it can be made upon a large and representative sample. Variations in toughness values were studied in certain cases.

The abrasion and toughness tests were performed according to the standard tests adopted by this Society.[1]

An abrasion test sample was considered as consisting of 50 pieces of rock of equal size, cubical in shape and weighing in the aggregate 5 kg. Such a sample was approximated as closely as possible. A variation of three or four from the 50 pieces and of 10 g. from the total 5 kg. weight was allowed. The charge after preparation was washed to free it from dust and loosely adhering splinters, dried and the weight adjusted to within the allowable limit. It was then run for 10,000 revolutions in the Standard Deval Abrasion Machine at the rate of 33 revolutions per minute. After the run the sample was thrown on a 16-mesh sieve, washed free of dust, dried and weighed. From the difference between the original and the final weights, the percentage of wear was calculated.

Test cylinders for the toughness test were prepared from diamond drill cores. These cores were 25 mm. in diameter with a variation within 1 mm. Cores were drilled both parallel to and across the structural planes of the sample block of rock when such planes were visible. Approximate lengths were cut from the cores by means of a diamond saw and test cylinders 25 mm. long carefully prepared by grinding with carborundum on a grinding lap. Care was exercised in the case of the cylinders to secure parallel, plane ends. These cylinders were tested by the Page Impact Machine for Toughness. The average of three tests was reported as the toughness of the sample. Two values were reported for samples of sedimentary rocks corresponding to the toughness of the material parallel to and across the bedding planes. In a few cases however, where the sample blocks were small or difficulty was experienced in drilling cores of sufficient length, tests were made only on cylinders cut across the bedding planes.

---

[1] 1918 Book of A.S.T.M. Standards, pp. 623–627.

II. To secure information regarding the size of the mass of stone that can be fairly represented by one sample, experiments were conducted to determine:

(*a*) The variations in quality of rock masses which appear in the outcrop or excavation to be of the same character.

(*b*) The magnitude of variations which are liable to appear between the results of tests on samples collected close together within the same sedimentary formation but representing rock of apparently somewhat different character due to a change in horizon.

(*c*) The variations in the results of tests on samples collected in the same sedimentary formation but at points separated widely both vertically and horizontally.

(*d*) The variations in the results of tests on samples collected from different members of a series of igneous dikes of the same character but lying several miles apart.

Method of Collecting Samples.—In collecting samples for the abrasion test, care was taken to secure samples which fairly represented the entire face of the deposit being sampled. Equal numbers of pieces were broken from equal units of height of face. A sample for the abrasion test was made up of 55 pieces of the right size or a little larger. In a good many cases 110 pieces were uniformly collected from the face and separated in the laboratory by quartering into duplicate samples. In other cases two samples of 55 pieces were separately collected over the same face and at the same place. If there was reason to suspect that any definite section of a deposit contained material that possessed somewhat different qualities than stone from the other parts of the deposit, samples were taken to detect any such

TABLE I(*a*).—RESULTS OF ABRASION TESTS ON DUPLICATE SAMPLES SECURED BY QUARTERING IN THE LABORATORY 100 PIECES OF ROCK COLLECTED TOGETHER AT THE DEPOSIT.

Quarry No.	Type.	Wear, per cent.		Difference.
97	Potsdam sandstone	2.4	2.3	0.1
99	Beekmantown limestone	4.3	4.1	0.2
130	Beekmantown limestone	3.1	3.1	0.0
139	Basic igneous	2.5	2.2	0.3
141	Trenton limestone	4.2	4.0	0.2
142	Trenton limestone	4.0	3.8	0.2
142	Trenton limestone	3.2	3.0	0.2
149	Bostonite (igneous)	2.2	2.2	0.0
153	Tinguaite (igneous)	2.1	1.9	0.2
153	Trenton limestone	3.1	2.5	0.6
155	Nepheline syenite	1.8	1.8	0.0
156	Trenton limestone (altered)	2.6	2.7	0.1
157	Trenton limestone	4.6	4.2	0.4
158	Chazy limestone	3.2	3.0	0.2
158	Chazy limestone	3.0	2.8	0.2
161	Nepheline syenite	2.3	2.5	0.2
161	Essexite (igneous)	2.3	2.1	0.2
161	Metamorphosed limestone	3.4	3.6	0.2
162	Syenite	2.1	1.8	0.3
162	Metamorphosed limestone, Breccia	3.2	2.7	0.5
163	Essexite	2.5	2.5	0.0
164	Trenton limestone	3.0	3.0	0.0
164	Dike rock	2.1	1.9	0.2
164	Trenton limestone	3.4	3.3	0.1
165	Trenton limestone	3.5	3.4	0.1
167	Trenton limestone	3.5	3.1	0.4
168	Trenton limestone	3.9	4.5	0.6
168	Trenton limestone	4.0	4.4	0.4
168	Trenton limestone	4.0	3.8	0.2

difference. Corresponding to each abrasion sample, toughness blocks representing each important lithological phase of the stone in the deposit were collected. In sampling crushed stone, material was taken from the stock pile of large sizes so that pieces with fresh edges could be prepared for the abrasion test.

Experimental Data.—The results of tests are arranged in tables to correspond to the sections mentioned under "Scheme of Experimentation."

Discussion of Results.—Table I (*a*) shows the difference observed between values for the per cent of wear for pairs of samples of the same material. The average difference is 0.2. There does not seem to be any decided correlation between increase in differences and increase in the percentage of wear of samples. It is probable, therefore, that a value for the percentage of wear of a sample will not differ from the result for an identical sample by more than 0.2 because of errors arising through laboratory manipulation.

TABLE I(*b*).—RESULTS OF ABRASION TESTS ON DUPLICATE SAMPLES COLLECTED SEPARATELY AT THE SAME POINT AT THE DEPOSIT.

Quarry No.	Type.	Wear, per cent.		Difference.
146	Trenton limestone	3.6	3.6	0.0
153	Tinguaite	2.1	2.2	0.1
153[a]	Trenton limestone	3.4	3.5	0.1
154	Trenton limestone	4.2	4.5	0.3
158	Chazy limestone	3.3	3.1	0.2
164	Trenton limestone	3.7	3.9	0.2

[a] Duplicate samples from a stock pile.

Table I (*b*) shows the differences which have been found to appear between the results of tests on abrasion samples collected separately but to represent the same material. These differences should be in each case the sum of differences due to laboratory manipulation as demonstrated by Table I (*a*) and the differences introduced by separate sampling. The average difference is, however, again about 0.2.

Table I (*c*) shows the differences observed between results of abrasion tests on samples collected from the rock in place in a quarry and from the stock piles of crushed product being produced at the quarry. It was thought possible that consistently lower percentages of wear would be obtained on the crushed product due to the elimination in the crushing and screening process of more or less of the softer parts of the natural rock. However, results for the crushed products are seen in the table to be as often higher as lower than the corresponding tests for the rock in place. In two cases, however, where decidedly lower results are observed for tests on the crushed stone, the rock in place was noted to contain a considerable amount of shaly partings between the beds. The elimination of this material during crushing probably accounts for the rather large differences. The average of the differences given in Table I(*c*) show that the probability is that the percentage of wear of a sample collected from a crushed rock stock pile will not differ from the

TABLE I(*c*).—COMPARISON OF RESULTS OF ABRASION TESTS ON SAMPLES COLLECTED TO REPRESENT THE MATERIAL OCCURRING IN A QUARRY AND TO REPRESENT THE CRUSHED PRODUCT PRODUCED FROM THE QUARRY.[b]

Quarry No.	Type.	Wear, per cent.		Difference.
		Sample from Quarry.	Sample from Stock Pile.	
38	Chazy limestone	4.0	3.8	0.2
142	Trenton limestone	3.9	3.1	0.8
144	Black River	3.7	4.5	0.8
145	Trenton limestone	3.6	3.8	0.2
153	Tinguaite	2.0	2.2	0.2
153	Trenton limestone	2.8	3.4	0.6
157[a]	Trenton limestone	5.8	4.4	1.4
158	Chazy limestone	2.9	3.1	0.2
159	Tinguaite	2.0	1.9	0.1
164	Trenton limestone	3.4	3.4	0.0
165	Trenton limestone	3.6	3.5	0.1
166	Tinguaite	2.0	2.3	0.3
167[a]	Trenton limestone	4.0	3.3	0.7
168	Trenton limestone	4.1	3.9	0.2

[a] Shaly partings prominent in these samples.

[b] In cases where several abrasion tests were made on rock in place the average value is given.

Table II(*a*).—Results of Abrasion Tests on Samples Collected at Various Points in a Sheet of Tinguaite, City of Montreal, Que. Samples taken over an Area of at Least One-Quarter Square Mile.

Quarry No.	Wear, per cent.
153	2.0
159	2.0
160	2.0
166	2.0

Results of Abrasion Tests on Samples Collected over the Face of the Quarry of the Canada Crushed Stone Corporation, Dundas, Ont. Each Sample was taken so as to Represent the 50 ft. of Strata Exposed in the Face. Points of Sampling were Spaced at Horizontal Intervals of Approximately 300 ft.

Sample.	Wear, per cent.
A	3.9
B	3.7
C	3.6
D	3.8
E	3.8

Table II(*b*).—Results of Abrasion Tests on Samples Collected at Various Points or at Different Levels in the Same Quarry to Represent Sections of the Deposit which Appeared to be Somewhat Different in Lithological Character from other Parts of the Deposit Exposed in the Quarry (Trenton Limestone Formation).

Sample No.	Wear, per cent.	Difference.	Remarks.
145	3.5(*a*), 3.6(*b*)	0.1	(*a*) Coarse uniform limestone. (*b*) Mixture of fine and coarse-grained limestone.
157	5.6, 5.3, 6.6	0.3 1.0 1.3	Variations in amount of shaly partings in the limestone.
165	3.3, 3.9	0.6	Two separate levels of a limestone quarry.
166	4.8(*c*), 3.3(*d*)	1.5	Separate levels. (*c*) Dense limestone, containing closely associated coarse-grained limestone. (*d*) Uniform dense black limestone.
168	4.2(*e*), 4.0(*f*), 4.2(*g*)	0.2 0.0 0.2	Different levels and different groups of beds (*e*) Limestone used for cut stone. (*f*) Coarse grained limestone with shaly partings. (*g*) Limestone strata containing fine-grained material.

TABLE II(*c*).—RESULTS OF ABRASION AND TOUGHNESS TESTS OF SAMPLES COLLECTED THROUGHOUT THE AREAS UNDERLAIN BY THE BEEKMANTOWN MAGNESIAN LIMESTONE, THE CHAZY LIMESTONE, THE BLACK RIVER LIMESTONE AND THE TRENTON LIMESTONE FORMATIONS IN THE VICINITY OF THE CITY OF MONTREAL, QUEBEC.

BEEKMANTOWN MAGNESIAN LIMESTONE FORMATION.

The total thickness of this formation is approximately 400 ft. The samples were taken over an area of about 8 sq. mi.

Sample No.	Thickness of Strata Sampled, ft.	Abrasion Test.		Toughness Test.[a]	
		Wear, per cent.	Character of Stone.	Toughness.	Character of Toughness Blocks.
130.......	5	3.1	Fresh bluish gray dolomite or magnesian limestone, fine gr., with calcite crystals.	16–19 10–12	Fine gr., uniform. Fine gr., uniform, prominent parting planes.
99.......	10	4.2	Fine gr. dolomite or magnesian limestone, dark, non-uniform, porous texture.	8–7	Fine gr., porous texture.
133.......	8	2.6	Dense, flinty dolomite or magnesian limestone, uniform, light blue-gray.	24–27	Very fine uniform gr.
134.......	6	2.4	Same char. as No. 133.	28	Same as No. 133.
92.......	9	3.3	Dense, dark dolomite or magnesian limestone, muddy looking, somewhat weathered.	11–11	Fine gr., siliceous (granular).

CHAZY LIMESTONE FORMATION.

The total thickness of this formation is approximately 250 ft. The samples were taken over an area of 60 sq. mi.

95.......	6	3.9	Dark gray, med. gr., granular, very fossiliferous.	5–6	Med. gr. uniform.
131.......	10	3.7	Same char. as No. 95.	4–6	Coarse loose gr., fossiliferous.
94.......	24	3.8	Same char. as No. 95.	6–8	Rather fine gr. uniform.
123.......	14	3.9	Fairly coarse gr.	5–7	Fairly coarse gr. uniform.
86.......	14	3.9	Coarse gr., fossiliferous.	6–8	Med. gr., non-uniform, parting planes prominent.
125.......	19	3.8	Coarse gr., fossiliferous, with some fine gr.	5–8	Coarse gr., fossiliferous, parting planes prominent.
88.......	32	3.9	Very fine to med. gr.	7–10 6–7	Almost dense. Fine to med. gr.
87.......	12	4.1	Med. gr., uniform, shaly partings.	5–7	Fine to med. gr., uniform dark parting planes.
148.......	8	3.9	Med. to coarse gr.	5–6	Med. gr., uniform.
129.......	7	4.2	Med. to coarse gr., fossiliferous	4–6	Coarse gr., uniform, dark parting planes.
83.......	3	4.2	Fine to coarse gr., fossiliferous.	7–10	Fine to coarse gr., fossiliferous.

NOTE.—Abbreviations used in Table: gr. = grain; med. = medium; char. = character.

[a] The two toughness values refer to the average toughness of cylinders cut parallel to and across the bedding planes of the rock respectively.

TABLE II(*c*).—*Continued.*

CHAZY LIMESTONE FORMATION.—*Continued.*

Sample No.	Thickness of Strata Sampled, in ft.	Abrasion Test.		Toughness Test.[a]	
		Wear, per cent.	Character of Stone.	Toughness.	Character of Toughness Blocks.
127.......	8	3.3	Med. gr., fairly uniform, some fossils.	5–6 6–9	Coarse gr., non-uniform. Med. gr., more uniform.
128.......	6	4.5	Same char. as No. 127.	4–7	Med. to coarse gr., shaly partings.
85.......	7	4.5	Same char. as No. 127	4–6	Fairly coarse gr., uniform,
80.......	25	5.6	Fine gr .to coarse gr., fossiliferous.	5–5 8	Coarse gr. Fine gr.
81.......	12	5.8	Same char. as No. 80.	3–4	Coarse gr.
93.......	10	4.9	Same char. as No. 80.	3–5	Coarse gr.
90.......	22	5.1	Same char. as No. 80.	4–5	Coarse gr.
89.......	24	4.2	Same char. as No. 80.	5–8	Fine to med. gr.
79.......	25	5.0	Med. to coarse gr., granular.	5–7	Med. gr.
82.......	5	5.2	Med. to coarse gr., granular.	5–9	Coarse gr.
151.......	11	4.2	Med to coarse gr., granular.	5–6 6–7	Coarse gr. Med. to fine gr.
143.......	11	4.3	Med. to coarse gr., granular.	6–8 5–6	Fine gr. Med. to coarse gr.

BLACK RIVER LIMESTONE FORMATION.

The total thickness of this formation is approximately 75 ft. The samples were taken over an area of about 5 sq. mi.

124.......	12	2.3	Dark, dense limestone, splintery, with some light gray med. gr. material.	8–10	Dense.
136.......	35	3.2	Limestone, about same char. as No. 124.	7 7 7	Fine grained. Fine grained. Dense to fine grained.
126.......	6	3.1	Dark, very fine gr. limestone, dense, splintery; a little coarse gr. material.	5–7	Med. gr., uniform.
132.......	12	2.8	Same char. as No. 126.	6–8	Dense, non-uniform texture.
91.......	10	3.6	Dark dense, somewhat shaly.	11–12 23–18	Dense to fine gr. Fine gr.
144.......	22	3.7	Limestone about same char. as No. 91.	9–9 9–9	Dense. Dense.

NOTE.—Abbreviations used in Table: gr = grain; med. = medium; char. = character.

[a] The two toughness values refer to the average toughness of cylinders cut parallel to and across the bedding planes of the rock respectively.

TABLE II (*c*).—*Continued.*

TRENTON LIMESTONE FORMATION.

The total thickness of this formation is approximately 500 ft. The samples were taken over an area of about 50 sq. mi.

Sample No.	Thickness of Strata Sampled, ft.	Abrasion Test.		Toughness Test.[a]	
		Wear, per cent.	Character of Stone.	Toughness.	Character of Toughness Blocks.
140.......	9	5.7	Coarse gr., shaly partings.		
141.......	10	4.1	Med. gr.	6–6	Coarse gr.
152.......	2	3.6	Fine to med. gr.	3–6	Fine gr.
138.......	9	3.4	Dense (top beds).	6–8	Dense.
138.......	12	4.3	Coarse gr. (lower beds).	5–7	Med. to coarse gr.
147.......	24	4.4	Med. gr., muddy looking streaks and shaly partings.	6–6 6–7 5–7	Med. gr. Fine gr. Coarse gr.
145.......	17	3.5	Fine gr. compact, some coarse beds.	5–7 7–8	Coarse gr. Fine gr.
146.......	20	3.6	Fine to med. gr., some shaly partings.	10–11 4–6 4–6	Med. gr. Fine gr. Fine gr., somewhat weathered.
142.......	25	3.9	Same char. as No. 146.	8–9 7–8	Fine to coarse gr. Fine gr.
150.......	12	5.6	Fine to med. gr., shaly partings, thin bedded.	4–8	Dense to fine gr., shaly partings.
137.......	34	3.5	Dense, non-uniform, with shaly partings; med. gr., very coarse gr., fossiliferous.	4–5 6–7	Med. gr. Very fine gr.
168.......	20	4.2	Fine to med. gr., with shaly partings; coarse grain.		
165.......	15	3.6	Fine to med. gr., with shaly partings.		
167.......	14	4.0	Dense, med. gr., with shaly partings; coarse gr.	9	Dense.
164	35	3.4	Med. to fine gr., with shaly partings; coarse gr.	4–6	Very coarse gr., fossiliferous.
154.......	37	4.3	Med. gr., med. to fine gr., with shaly partings.	7–7 6–8 5–8	Fine gr. Fine to very coarse gr., fossiliferous. Very fine gr.
157.......	25	5.8	Med. to fine gr., with shaly partings.	7 6 4–6 3–7	Coarse gr., fossiliferous. Fine gr., shaly partings. Coarse gr., fossiliferous. Very fine gr., some shaly partings.
153.......	10	3.1	Dense, dark uniform.	11	Dense.
166.......	12	4.0	Dense, dark uniform.	9–11	Dense.

NOTE.—Abbreviations used in Table: gr. = grain; med. = medium; char. = character.

[a] The two toughness values refer to the average toughness of cylinders cut parallel to and across the bedding planes of the rock respectively.

percentage of wear of a sample from the corresponding rock in place by more than 0.4.

Table II (*a*) is self-explanatory. It indicates that when the character of the stone throughout a deposit appears to be uniform, the results of abrasion tests show little variation. The sheet of tinguaite to which the first part of the table refers is an igneous intrusion of uniform material sampled at points up to 500 yd. apart. The second part of the table refers to a deposit of dolomite 50 ft. thick, of uniform appearance, sampled over a distance along the strike of about 1400 ft.

Table II (*b*) shows the differences that have been observed between the results on abrasion samples collected in the same quarry, to represent apparent changes in the quality of the stone.

Table II (*c*) shows the results of abrasion and toughness tests, with remarks on the character of the stone, for samples collected throughout areas underlain by rock of the same sedimentary formation. Except in the case of the Beekmantown formation, the samples are well distributed throughout the different horizons of the formation as well as laterally throughout the area. The order of arrangement of the samples in the table for a formation, though seemingly haphazard, is more or less according to the location of the deposits where the sampling was done. Results of samples from the same neighborhood are placed together. In cases where several abrasion tests were made on bedrock from the same quarry the average per cent of wear is given.

In examining the variation displayed by the results, the average value for the percentage of wear and the toughness, and the average deviation of the individual values from this average, have been calculated for each group of results. They are as follows:

FORMATION.	AVERAGE PERCENTAGE OF WEAR AND AVERAGE DEVIATION.	AVERAGE TOUGHNESS AND AVERAGE DEVIATION.
Beekmantown	3.1 ± 0.5	16 ± 7
Chazy[1]:		
Montreal Island	3.9 ± 0.1	7 ± 1
Ile Jesus	4.6 ± 0.5	6 ± 1.5
Black River	3.1 ± 0.4	8 ± 1.5
Trenton	4.1 ± 0.6	7 ± 1.5

---

[1] The area underlain by the Chazy formation has been divided because the results on samples coming from two separate areas show decidedly different degrees of variation.

Table II (*d*) shows the results of abrasion and toughness tests for samples collected from a series of large diabase dikes trending east and west and outcropping at intervals through a distance of 60 miles on the north shore of the Ottawa river. These dikes are all of the same geological age and their mineral composition and structure are the same; the only apparent difference lies in a slight variation in the average size of the grain. They vary in width from 100 to 300 ft. and up to one mile in outcrop length. They all trend in the same direction and are arranged in the table according to position from west to east. Each dike was sampled by breaking off pieces as nearly as possible equidistant from each other across the direction of the dike. Only one toughness block was sampled in this series. Their average percentage of wear as derived from the tables is 3.2; their average toughness is 13. The average deviation from the average percentage of wear is 0.2; the average deviation from average toughness is 2.

TABLE II(*d*).—SERIES OF DIABASE DIKES.

The dikes are all of diabase and vary in width from 100 to 300 ft. In most cases they were sampled across the full width of the dike.

Sample No.	Abrasion Test; Wear, per cent.	Toughness.	Character of Stone.
304	4.0	10	Coarse grained.
305	2.8	8	Coarse grained.
62	3.2	12	Medium grained.
138	3.7	16	Medium grained.
156	3.0	17	Medium grained.
158	3.4	15	Medium grained.
164	3.2	10	Coarse grained, badly altered.
164	2.8	12	Coarse grained, fresher rock than above.
172	3.0	16	Fine grained.
177	3.2	12	Fine grained.
183	3.2	14	Medium grained.
187	3.4	13	Medium grained.
188	3.0	14	Medium grained.
191	3.4	11	More basic than average.

Conclusions.—The following conclusions may be drawn from the results of the investigation on bedrock:

1. The results of an abrasion test expressed as per cent of wear is liable to an error of 0.2 per cent due to variations caused by laboratory procedure.

2. No additional error is introduced into the results of abrasion tests by the process of sampling when samples are collected in the manner outlined above.

3. Results of abrasion tests on rock in place in a deposit represent, within a probable difference of 0.4, the percentage of wear that will be shown by a crushed product produced from the deposit.

4. In the case of deposits consisting of stone of a very uniform character and appearance, the results of abrasion tests on samples taken at one point in the deposit can be regarded as representing within the probable error due to laboratory manipulation, the percentage of wear of the stone over quite a considerable area, at least a quarter of a square mile.

5. It is possible to assign average values and fairly narrow limits of variation of this value for the percentage of wear and the toughness of the material occurring in a limestone formation covering areas up to 50 and 60 square miles, and with thicknesses up to 500 ft., even though stone varying in character is included in the formation. These values and limits will include the majority of results of tests made on samples collected throughout the formation and its various horizons.

These limits should define the maximum variation of the results of abrasion and toughness tests made on samples collected from a quarry in a limestone formation to represent the material produced from the quarry as operations are extended from year to year. They should assist in determining at what intervals apart vertically and horizontally it is necessary to sample formations consisting mainly of limestone or dolomite in order to arrive at their average percentage of wear and toughness values, and variations from such values.

6. The results of abrasion and toughness tests over a series of diabase dikes of the same age and structure reveal very uniform results in deposits of the same grain. A change in the average size of grain affects the toughness value slightly. The

number of samples taken in dikes of this character need therefore not be great even though they cover large areas, if structural conditions and the texture and degree of alteration of the stone remain the same.

SAMPLING AND TESTING OF DEPOSITS OF BOULDER AGGREGATES OR FIELD STONE.

The boulder aggregates here referred to are the deposits of boulders of glacial origin which are so widely distributed over the eastern half of Canada and the northeastern portion of the United States. Over large areas these boulders have been piled into fences and heaps and they form a comparatively cheap and often valuable source of road stone. In making field surveys of these materials it was found that over any given area the aggregates were made up of a number of rock varieties varying in some cases very greatly in their road-making qualities. The percentages of these varieties present in any one fence or pile also varied from one part of an area to another, so that a great number of fences would have to be sampled to arrive at the average value of the whole deposit. It was discovered, however, that the rock varieties present could in most cases be classified into two or three general series or types, each one of which was readily distinguished from the others in the field and was of the same average durability over a wide area. Field estimates of the proportion of types present in the fences can be made rapidly and in detail by comparatively unskilled workers. Experiments were therefore conducted to see whether a relation could be established between the abrasion test on each of a series of rock types occurring in boulder aggregates and the results of the test on combinations of these types. The results have shown that the percentage of wear of a mixture of several rock types is a simple function of the percentage of wear of each rock type and of the proportions, expressed in per cent, in which the types are present in the mixture. If the percentages of wear of the various types are expressed by $W_1, W_2 \ldots W_n$ and the percentage proportions in which they occur in the mixture by $C_1, C_2 \ldots C_n$, the percentage of wear of the mixture W_m is given by the formula

$$W_m = \frac{\Sigma C W}{100}.$$

TABLE III.—TESTS OF FIELD STONE.

CORNWALL DISTRICT, ONTARIO.

Type.	Wear, per cent.	
No. 1—Igneous rock	2.8, 2.5	aver. 2.7
No. 2—Potsdam sandstone	2.4, 2.2	" 2.3
No. 3—Black River limestone	3.6, 3.6	" 3.6
MIXTURE OF	ACTUAL.	CALCULATED.
50 per cent Type No. 1 and 50 per cent Type No. 2	2.8	2.5
" " " " 1 " " " " " 3	3.0	3.1
" " " " 2 " " " " " 3	3.0	2.9
47 " " " 1, 28 per cent Type No. 2, 25 per cent Type No. 3	2.7	2.8

MONTREAL ISLAND, QUEBEC.

Type.	Wear, per cent.	
No. 1—Igneous rock	2.4, 2.9	aver. 2.7
No. 2—Coarse Chazy limestone	4.2, 5.1	" 4.7
No. 3—Dense Black River limestone	3.7, 3.7	" 3.7
No. 4—Coarse Chazy limestone	4.5, 5.1	" 4.8
No. 5—Uniform fine-grained Chazy limestone	3.6, 3.0	" 3.3
MIXTURE OF	ACTUAL.	CALCULATED.
35 per cent Type No. 1, 37 per cent Type No. 2, 27 per cent Type No. 3	3.6	3.7
67 " " " 2, 33 " " " 3	3.5	4.0
50 per cent Type No. 4 and 50 per cent Type No. 5	4.4	4.1

VAUDREUIL DISTRICT, QUEBEC.

Type.	Wear, per cent.	
No. 1—Igneous rock	4.3, 3.5	aver. 3.9
No. 2—Trenton limestone	5.9, 5.6	" 5.7
No. 3—Fine-grained Potsdam sandstone	2.2, 2.1	" 2.2
No. 4—Beekmantown limestone	3.3, 3.2	" 3.3
MIXTURE OF	ACTUAL.	CALCULATED.
50 per cent Type No. 1 and 50 per cent Type No. 2	4.7	4.8
" " " " 1 " " " " " 3	3.0	3.1
" " " " 1 " " " " " 4	3.6	3.6
" " " " 2 " " " " " 3	3.8	4.0
" " " " 2 " " " " " 4	4.6	4.4
" " " " 3 " " " " " 4	2.8	2.8
25 per cent Type No. 1, 25 per cent Type No. 2, 25 per cent Type No. 3, 25 per cent Type No. 4	3.7	3.8

MONTREAL ISLAND, QUEBEC.

Type.	Wear, per cent.	
No. 1—Igneous rock	2.9, 2.7	aver. 2.8
No. 2—Fine-grained Potsdam sandstone	2.1, 2.4	" 2.3
No. 3—Coarse-grained Potsdam sandstone	6.1, 6.3	" 6.2
MIXTURE OF	ACTUAL.	CALCULATED.
No. 1—50 per cent Type No. 1 and 50 per cent Type No. 2	2.6	2.6
No. 2—" " " " 1 " " " " " 3	5.5	4.5
No. 3—" " " " 2 " " " " " 3	4.8	4.3
No. 4—33⅓ " " " 1, 33⅓ per cent Type No. 2, 33⅓ per cent Type No. 3	4.3	3.8

By sampling and testing the three or four types which make up a deposit, therefore, it is possible to calculate the percentage of wear of any of the combinations of these types found in any one fence or groups of fences. An accurate estimate of the quality of boulder deposits of large size and extent can be arrived at by this method in a comparatively short time.

Details of the Experiments.—In Table III are presented the results of experiments conducted in four different field stone areas. In each of these, separate samples were collected from each of the types mentioned and the results of tests upon combinations of the types are compared with results calculated by the formula given above. It will be seen that they are practically identical. The "igneous rock" type mentioned in each of the areas consisted of a combination of gneisses and igneous rocks made up of a number of rock varieties but with a nearly constant average percentage of wear for the combination throughout the area in question.

The last series of results form an exception to the rule. In each mixture where the coarse-grain sandstone forms a constituent, the mixture gives a higher percentage of wear than the calculated value. This material evidently wears faster in the presence of other harder material. It is interesting to note that if mixture No. 4 is considered as consisting of equal parts of mixtures Nos. 1, 2, and 3, the actual value of the percentage of wear for mixture No. 4 can be calculated from the actual values of the percentage of wear of the three constituent mixtures:

$$\frac{33.3(2.6+5.5+4.8)}{100}=4.3 \text{ per cent.}$$

Conclusions.—The following conclusions may be drawn from the investigation on boulder aggregates:

It was found that boulder deposits in any one area consist of many combinations of three or four rock types of fairly uniform durability, and that the percentage of wear of any combination of the rock types found in deposits of boulder aggregates could be calculated by the following formula if the percentages of wear of each of the rock types were known:

$$W_m=\frac{\Sigma C W}{100},$$

in which $W_1, W_2 \ldots . W_n$ = percentages of wear of the various rock types, and $C_1, C_2 \ldots . C_n$ = percentage proportions in which the rock types are present in the combinations.

TABLE IV.—DIFFERENCES OBTAINED IN PERFORMING DUPLICATE GRANULOMETRIC ANALYSES OF SANDS.

Sample No.		Differences between Percentages rctained on Mesh No.							Percentage Error.
		8	14	28	48	100	200	pass 200	
1		8.0	1.7	4.1	1.5	0.6	0.1	0.1	0.37 0.06
8		3.21	0.22	0.93	0.26	0.17	0.03	0.0	0.20 0.14
10		1.1	0.35	0.22	3.63	4.94	0.22	0.21	0.17
17	Quartered	3.24	2.51	1.55	3.06	1.14	0.06	0.01	0.23 0.18
	With sampler	2.43	0.39	0.59	1.54	0.50	0.08	0.03	0.16 0.14
20		7.59	1.12	2.20	0.55	2.00	0.12	0.05	0.05 0.07
23	Quartered	7.63	2.20	2.82	1.60	0.78	0.14	0.10	0.18 0.28
	With sampler	1.44	0.15	1.05	0.16	0.16	0.04	0.11	0.20 0.06
44(*a*)		2.00	1.52	0.17	1.65	0.98	0.39	0.78	0.16 0.04
44(*b*)		5.02	2.20	1.44	2.29	5.89	0.32	0.19	0.07 0.21
45(*e*)		0.05	0.07	0.33	0.93	0.84	7.50	9.60	0.15 0.02
47		2.89	1.52	1.13	2.72	0.58	0.04	0.10	0.13 0.09
48		1.7	0.0	0.7	1.8	0.6	0.3	0.1	0.16 0.09
58		3.82	2.21	1.37	0.41	0.03	0.02	0.22	0.04 0.02
63		4.05	0.92	0.74	1.83	0.27	0.12	0.08	0.22
67		1.44	0.59	0.18	1.37	3.1	0.19	0.18	0.11 0.02
100		0.32	0.29	0.87	0.0	0.01	0.51	0.78	0.06 0.21
Average difference		3.29	1.29	1.20	1.49	1.33	0.594	0.74	....
Average error		....	....	....	....	....	....	....	0.13

VARIATIONS IN GRAVEL AND SAND DEPOSITS.

The texture or grading of a gravel is the characteristic used more generally than the results of other laboratory tests in judging its value for the various forms of road construction in which it is incorporated. The results of a study of the variation in grading show great liability to variation due to laboratory manipulation and a considerable amount of variation in texture within the same deposit. These results apply to one deposit only, however, and no general deductions as to the variations in other deposits can be drawn from them.

Table IV gives the differences in percentages by weight retained on each sieve, obtained in making granulometric analyses in the laboratory of two portions of the same sample of sand by standard methods. The two portions compared were in each case obtained from the same sample of sand, weighing from 20 to 40 lb., either by quartering or by means of a mechanical sampler. In the case of samples Nos. 17 and 23 two portions of each were obtained by quartering and two by the sampler, the results from the sampler being the closer. The last column in the table gives the percentage of error occurring in the opera-

TABLE V.—GRANULOMETRIC ANALYSES OF GRAVELS FROM DIFFERENT PARTS OF THE SAME DEPOSIT. EXTENT OF AREA, 800 ACRES.

Sample No.	Percentage Gravel Retained on ¼-in. Sieve.	Total Percentage of Sand Retained on			Percentage Passing 48 Mesh.
		8 Mesh.	20 Mesh.	48 Mesh.	
42	14	22	55	93	7
43	53	47	60	88	12
44(*a*)	10	10	34	73	17
44(*b*)	16	8	46	93	6
45(*a*)	66	49	69	90	10
45(*c*)	24	41	70	92	8
45(*d*)	59	34	34	78	22
45(*f*)	39	31	46	85	15
45(*g*)	11	13	39	94	6
45(*h*)	13	12	38	92	8
45(*j*)	16	25	67	92	8
45(*k*)	37	22	47	88	11
45(*m*)	19	19	52	94	6
47(*b*)	38	18	52	91	9
47(*a*)	7	19	57	91	9
48(*a*)	44	20	58	90	10
48(*c*)	22	18	54	92	8
48(*d*)	15	18	46	93	7
49	3	10	46	92	8
50	17	37	73	92	8
45(*b*)	0	0	4	31	69[e]
45(*e*)	0	1	3	17	83[e]

Nos. 45(*b*) and 45(*e*) are analyses of silt from the same deposit.

tion as determined by the difference in weight of the sample before sifting and the sum of the weights of the sand finally on the screens.

In Table V are given the results of granulometric analyses of samples taken from 22 points in a deposit of gravel and sand of the outwash glacial type. The samples are fairly well distributed over the whole deposit. They were taken over from about 4 to 10 ft. of vertical face of the gravel. Two of the samples were of silts or very fine sand overlying the gravel and sand in places and easily distinguished from it. Five samples were tested in the laboratory and 17 in the field. The field analyses were obtained by sifting by hand and volumetric measurements. Field and laboratory analyses were compared by taking duplicate samples at 13 points and analyzing by both methods. It was found that the total amounts retained on the $\frac{1}{4}$-in. sieve by the field method varied by an average of 5 per cent from that by the laboratory method, the field results being in some case higher and in others lower. The same results held for total amount passing the $\frac{1}{4}$-in. and held on the No. 8 sieve. The total amount of sand, that is material passing the $\frac{1}{4}$-in. mesh and held on the Nos. 20 and 48 sieves, averaged respectively 11 and 5 per cent higher by the field than the laboratory method and the amount passing the No. 48 sieve averaged 4 per cent lower. The results of field analyses for total amount of sand retained on the No. 20 and No. 48 mesh and passing the No. 48 mesh was corrected by subtracting 11 and 5 and adding 4 per cent respectively. The results show great variation in the grading of the gravels and sands within the deposit.

Conclusions.—A large variation was found between the results of duplicate granulometric laboratory analyses on the same sack of gravel. The variation in texture over one deposit of gravel of 800 acres was found to be large.

DISCUSSION.

Mr. Mattimore. Mr. H. S. Mattimore (*by letter*).—This paper is especially important in that it takes up a line of work upon which very little has been published. All highway engineers should realize the importance of sampling, especially of the natural materials treated in this paper. Sampling is the basis of the selection of these materials and in order to give the proper value to the tests, the sample must be representative of the supply.

Table I (*a*) of the paper shows a very close check in the abrasion test; in fact, the author's conclusions of a difference of 0.2 per cent of wear is a closer check than could be expected as a general average. The method of preparing the specimens and the final shape of the stone as placed in the cylinder are the principal factors that affect the results. With the same operator using the same methods, errors from these factors can be reduced to a minimum. The results from different laboratories, however, are likely to show a larger difference.

In the accompanying Table I are given the results of some experiments made by the writer to ascertain the degree of accuracy of the stone tests. Twenty test results are reported, ten on syenite and ten on dolomite. The samples of each material were as nearly uniform as could be obtained. In order to secure average results, no two samples were tested at the same time. Several days were allowed to intervene between the testing of each sample.

This table shows a somewhat greater difference in percentage of wear than that given in the authors' paper, but it agrees with the authors' experiments in indicating that the abrasion test can be checked with greater accuracy than the toughness test. The existence of natural seams or shock fractures in rock affects the toughness test to a greater extent than the abrasion test. These defects, moreover, are difficult to detect and therefore almost impossible to avoid.

One surprising feature in this part of the paper—Table II (*c*) —is the uniformity of quality indicated by tests of the same rock

Mr. Mattimore. formation regardless of a difference in crystallization. The prevailing opinion seems to have been that, especially in limestone, there would be a large variation in quality between the dense close-grained, and the coarse crystallin varieties. There is a doubt in the writer's mind whether the present abrasion machine would indicate this difference in quality which might exist.

The section treating on the sampling and testing of field stone will especially appeal to engineers in sections where these deposits are the most economical to use. The authors' method of using calculated values for abrasion computed with the given formula is indeed helpful. It is less difficult to make separate tests on the material and compute the composite value, than to try and divide the one charge into the different percentages; moreover, this calculated abrasion would allow for a change in value if a more detailed survey should indicate an error in percentages given in the first investigation.

TABLE I.

Syenite.				Dolomite.			
Percentage of Wear.		Toughness.		Percentage of Wear.		Toughness.	
Observed Values.	Deviation from Average.	Observed Values.	Deviation from Average.	Observed Values.	Deviation from Average.	Observed Values.	Deviation from Average.
3.6	+0.4	14.0	+2.3	4.7	+0.2	6.0	−0.6
2.8	−0.4	8.5	−3.2	5.0	+0.5	7.0	+0.4
3.3	+0.1	12.5	+0.8	4.4	−0.1	6.0	−0.6
3.3	+0.1	11.5	−0.2	4.1	−0.4	6.5	−0.1
2.9	−0.3	11.0	−0.7	4.8	+0.3	6.5	−0.1
3.3	+0.1	13.0	+1.3	4.5	0.0	7.5	+0.9
3.0	−0.2	12.5	+0.8	4.4	−0.1	6.5	−0.1
3.7	+0.5	10.5	−1.2	4.8	+0.3	7.0	+0.4
2.6	−0.6	12.0	+0.3	4.6	+0.1	6.0	−0.6
3.9	+0.7	11.5	−0.2	4.2	−0.3	7.0	+0.4
Average. 3.2	.....	11.7	.....	4.5	.....	6.6	.....

AN ABRASION TEST FOR STONE, GRAVEL AND SIMILAR AGGREGATES.

By H. H. Scofield.

SUMMARY.

It has been found that the standard Deval test for road materials is somewhat misleading in its results due to the retention within the abrasion chamber of the dust worn from the charge.

This dust cushion would obviously decrease the rate of loss during the later stages of the test and would be more noticeable in tests of the softer materials than in those materials which yield little dust.

The test described in this paper is devised to do away with this objection, and also to furnish a more rapid and practical test as well as a simpler machine.

Various tests are shown to illustrate the action of the new apparatus upon rock and gravels.

AN ABRASION TEST FOR STONE, GRAVEL AND SIMILAR AGGREGATES.

BY H. H. SCOFIELD.

The resistance of stone and gravel or other road materials to the abrasive action of service must be recognized as an important quality. The careful and wise selection of such materials would be considerably aided by a rapid and efficient laboratory test. The results of such a test should, of course, be studied in connection with the important test, that of service.

In 1916,[1] the writer called attention to a seeming weakness in the standard Deval abrasion test for rock, in that the dust resulting from the abrasion is retained in the container and acts as a cushion to cut down loss in the later stages of the test. (See Figs. 1 and 2.) This is illustrated by the tests given in Table I, in which a medium stone and an extra soft stone were tested by the standard Deval machine.

TABLE I.—TESTS TO SHOW EFFECT OF DUST IN DEVAL ABRASION APPARATUS.

Kind of Test.	Wear, per cent.		Ratio of Soft to Medium.
	Medium Stone.	Extra Soft Stone.	
Deval Test, regular (10,000 revolutions)	5.28	10.3	1.95
Deval Test with all dust removed after every 1000 revolutions	10.7	25.8	2.41

It is evident that the ratio in Table I would be considerably larger if the container were so arranged as to remove the dust as fast as formed. This has been done with success in one or two laboratories.

A simple abrasion machine devised to do away with the objection as pointed out is shown in Fig. 3. The machine is a small type rattler in which the dust and chips abraded from the sample escape between the staves as fast as formed. The

---

[1] *Proceedings*, Indiana Engineering Society, 1916–17.

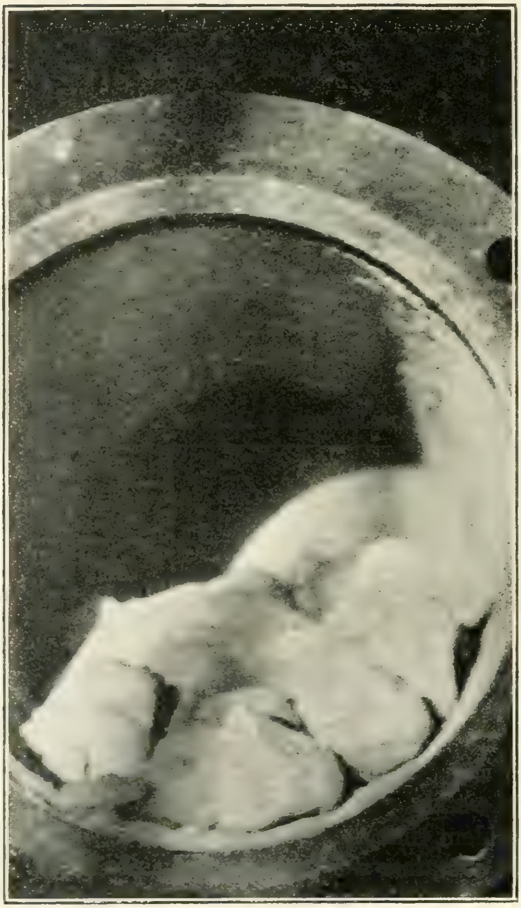


FIG. 1.—Interior of Deval Cylinder after Test, showing Dust Adhering to Stones and Surface of Cylinder.

opening between staves is $\frac{1}{16}$ in. The abrasion chamber is octagonal in shape with a volume equivalent to that of the Deval cylinder.

Fig. 4 illustrates stone taken from this abrasion apparatus, showing absence of dust.

Recent tests with this apparatus upon twelve Indiana limestones in the Laboratory for Testing Materials, Purdue University, are shown in Table II and graphically in Fig. 5. In general, the new test gives a greater range of results and a consequent better differentiation of quality. The effect of the dust cushion in the Deval test is apparent in the more or less regular increase in the ratio of the results of the new test to those of the Deval test as the stones tested vary from hard to soft.

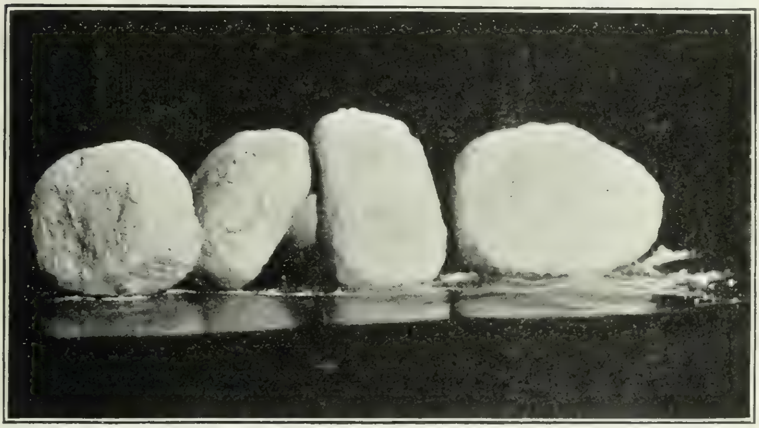


FIG. 2.—Stone as Taken from Deval Test, showing Dust Adhering.

It became apparent from these tests that to shorten the time to a practical limit, it would be necessary to use an abrasive agent and to cut down the size of sample from 5000 to 2500 g. It also appeared from further tests that the sample for the tests could be made more practical and useful if one-half were $\frac{1}{2}$ to 1 in. in size and one-half were 1 to 2 in. in size. The standardized test, as operated at the present time, is as follows:

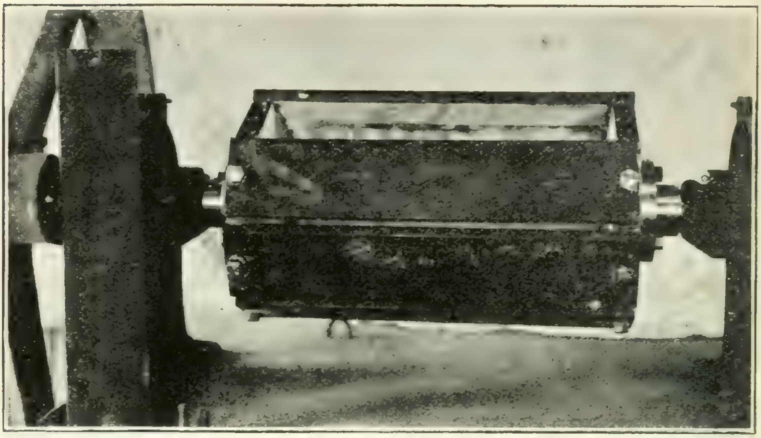


FIG. 3.—New Abrasion Apparatus without Its Dust Cover.

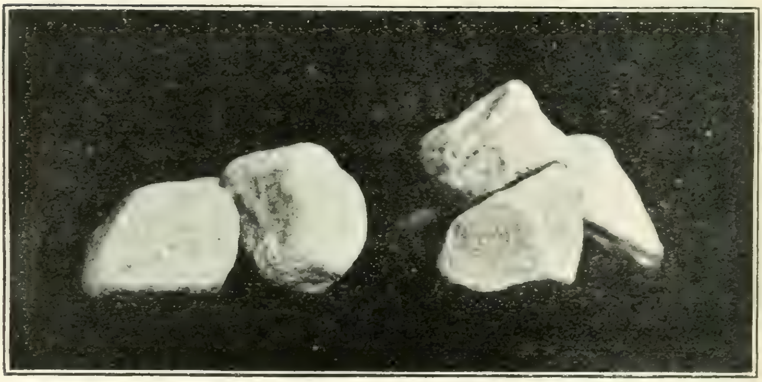


FIG. 4.—Stone as Taken from New Abrasion Apparatus, showing Absence of Dust.

TABLE II.—TESTS OF 12 TYPICAL INDIANA LIMESTONES WITH THE STANDARD DEVAL AND NEW ABRASION TEST APPARATUS.

SAMPLES 5000 G. EACH. TOTAL NUMBER OF REVOLUTIONS, 10,000; 30.5 R. P. M.

Sample No.	Wear, per cent.		Ratio of New to Deval Test.
	Deval Test.	New Test.	
1....................	3.5	8.1	2.3
2....................	4.15	9.1	2.19
3....................	3.9	9.6	2.46
4....................	3.76	9.7	2.58
5....................	3.6	10.3	2.86 (one test only)
6....................	3.0	10.5	3.5 (" " "
7....................	4.1	11.8	2.9 (" " "
8....................	5.56	14.1	2.54
9....................	6.0	14.7	2.45
10....................	6.05	16.3	2.70
11....................	6.00	20.2	3.36
12....................	10.3	35.2	3.42

TABLE III.—TESTS OF BROKEN STONE WITH THE NEW APPARATUS UNDER VARYING CONDITIONS AS TO CHARGE AND NUMBER OF REVOLUTIONS.

Sample.	Abrasive Charge.	Number of Revolutions.	Wear, per cent.	
			Medium Stone.	Soft Stone.
DEVAL TEST.				
50 pieces, 5 kg....................	None	10 000	5.28	10.3
NEW TEST.				
50 pieces, 5 kg....................	None	10 000	12.3	35.2
25 " 2.5 "....................	None	2 000	5.3	14.9
25 " 2.5 "....................	6, $1\frac{7}{8}$-in. Shot	2 000	6.0	17.1
25 " 2.5 "....................	" " "	4 000	10.0	27.1
25 " 2.5 "....................	" "	6 000	13.4	35.1
25 " 2.5 "....................	" " "	8 000	16.6	42.5
25 " 2.5 "....................	" " "	10 000	19.3	48.2
1 to 2-in. sizes, 2.5 kg............	" " "	2 000	7.3	19.3
1 to 2 " " 1.25 ".......... $\frac{1}{2}$ to 1 " " 1.25 "..........	" " "	2 000	9.7	24.6
$\frac{1}{2}$ to 1 " " 2.5 "............	" " "	2 000	9.9	23.0

The sample of stone or gravel or other road material consists of 2500 g., of which 1250 g. are from $\frac{1}{2}$ to 1 in. and 1250 g. are from 1 to 2 in. in size. The abrasive agent consists of six cast-iron spheres $1\frac{7}{8}$ in. in diameter as used in the rattler test for paving brick. The charge is given 2000 revolutions in the case of broken stone and 4000 revolutions in the case of gravel, at the rate of 30 revolutions per minute. The losses for both stone and gravel for this shortened test are approximately the same as for a full 5000-g. sample for 10,000 revolutions, without an abrasive charge.

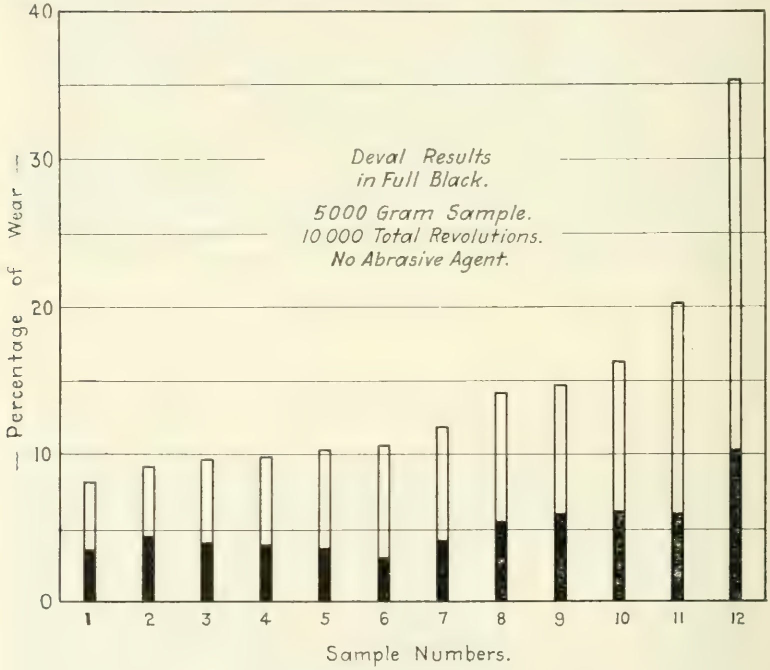


FIG. 5.—Tests of Limestones with Deval and New Abrasion Apparatus. See Table II.

RESULTS OF TESTS.

Table III gives the results of tests upon broken stone under different conditions as to charge and number of revolutions. The next to the last item gives the results of the standardized test with the new apparatus as arranged at present.

Table IV shows the results of the standardized test with the new apparatus upon gravels. For the purpose of comparison and study, the gravels were selected particles from the local gravel deposits synthetically grouped as shown. These results are also shown graphically in Fig. 6.

TABLE IV.—RESULTS OF THE STANDARDIZED TEST WITH THE NEW APPARATUS ON VARIOUS GRAVELS.

Gravel Content, percentage by Weight.					Wear, per cent.	
Trap.	Granite.	Quartz.	Limestone.	Sandstone.	2000 Revolutions.	4000 Revolutions.
100	0	0	0	0	0.4	1.08
0	100	0	0	0	1.48	2.60
0	0	100	0	0	2.04	3.48
0	0	0	100	0	2.24	4.52
0	0	0	0	100	15.52	23.04
50	5	5	40	0	1.5	2.5
50	5	5	35	5	3.2	4.5
50	5	5	30	10	4.0	5.9
50	5	5	20	20	5.2	9.0
50	5	5	10	30	7.0	10.5
50	5	5	0	40	10.0	14.0
40	5	5	50	0	1.5	2.9
35	5	5	50	5	3.0	5.5
30	5	5	50	10	4.5	7.5
20	5	5	50	20	6.0	9.7
10	5	5	50	30	9.4	14.0
0	5	5	50	40	12.0	17.2
15	5	5	75	0	2.1	3.8
10	5	5	75	5	3.3	5.6
5	5	5	75	10	5.0	8.4
0	5	5	75	15	6.0	9.3
2	2	2	75	19	8.0	10.8

Except where otherwise stated the results are the average of at least three tests.

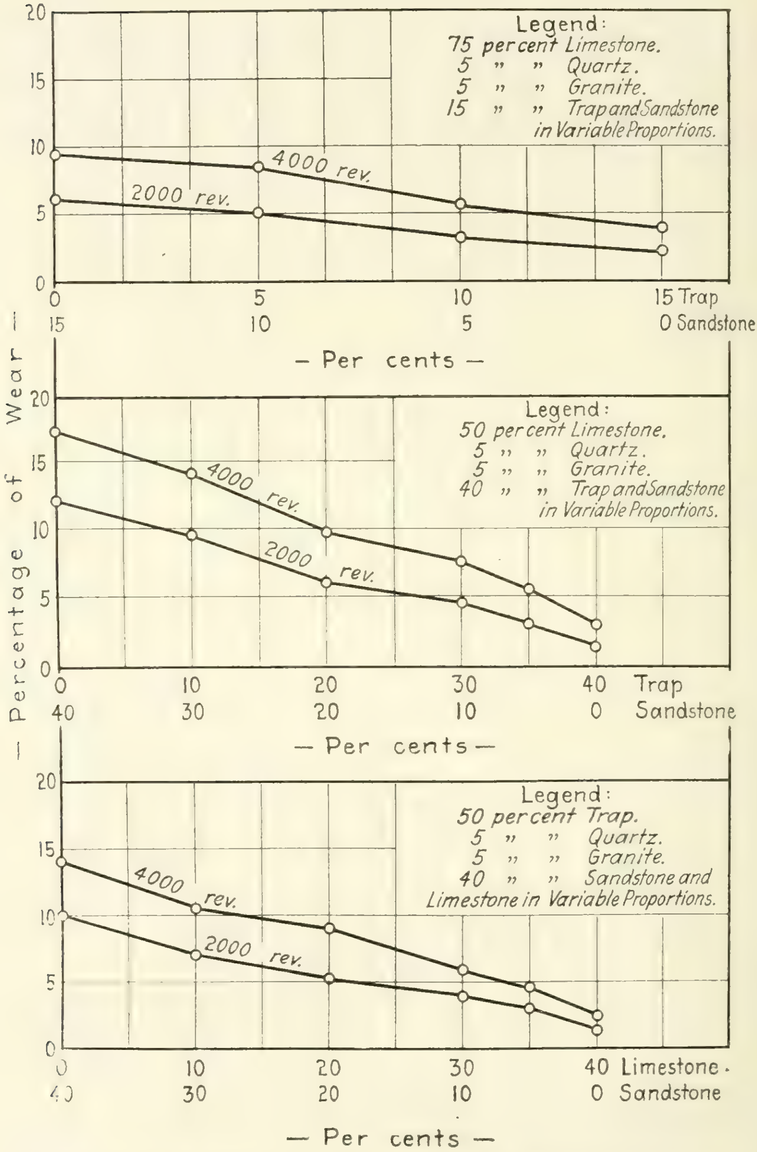


FIG. 6.—Tests of Synthetic Gravels with New Abrasion Apparatus as Standardized. See Table IV.

CONCLUSION.

The apparatus here described has been devised at the Laboratory for Testing Materials, Purdue University, to fill the need of a rapid and practical abrasion test for road materials of all kinds. The machine is simple in construction and acts upon the right principle by allowing the dust of abrasion to escape.

The tests of stone and gravel reported are given as representing certain local conditions. It is hoped that others will continue abrasion tests with this or a similar apparatus, especially in the field of gravels where very little testing has as yet been done.

DISCUSSION.

Mr. Mattimore.

MR. H. S. MATTIMORE (*by letter*).—The elimination of the dust cushion in the abrasion machine is an important factor which should be investigated by all highway testing engineers. Mr. Scofield's paper is of great importance in that connection and is worthy of study.

The writer has been investigating the abrasion test along this line for several years and the results are in the main a check on those obtained by the author. The machine illustrated in the accompanying Fig. 1, although different in design from that described by Mr. Scofield, accomplishes the same purpose of eliminating the dust cushion. This is done by slotting the standard abrasion cylinder. These slots are $\frac{1}{16}$ in. on the inside and $\frac{1}{4}$ in. on the outside to allow for machining or casting.

TABLE I.

ALL VALUES ARE PERCENTAGE OF WEAR.

Sandstone and Quartzite.		Limestone and Dolomite.	
Standard Cylinder.	Slotted Cylinder.	Standard Cylinder.	Slotted Cylinder.
4.8	6.8	5.2	13.2
4.6	6.6	3.4	5.0
6.0	7.0	5.0	7.6
2.0	6.0	5.0	10.8
2.8	4.8	4.4	10.2
3.6	10.6	3.2	9.2
6.6	13.6	5.6	11.2
4.0	7.0	6.4	11.6
5.4	10.4	4.6	14.0

In Table I are given the results of comparative tests in the standard and slotted cylinders on several classes of stone.

Mr. Mattimore.

All of these tests were run according to standard methods with a charge of 5 kg. of stone run for 10,000 revolutions.

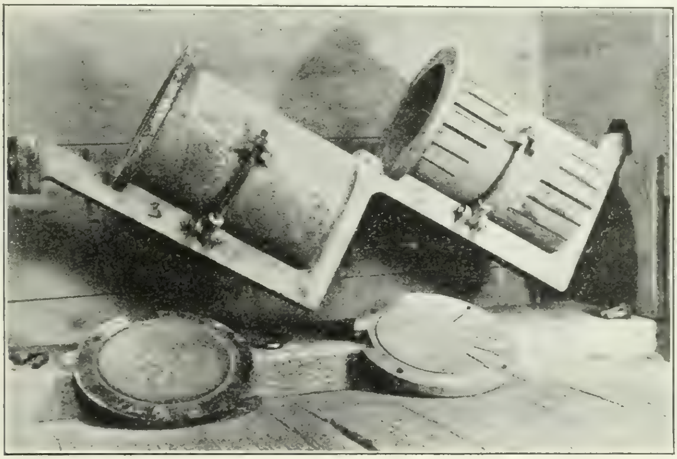


FIG. 1.—Abrasion Machine showing Cylinder Slotted to Eliminate Dust Cushion.

The results of a comparative test on the different cylinders with and without an abrasive charge are given in Table II. The charge consisted of six $1\frac{7}{8}$-in. cast-iron spheres.

TABLE II.

ALL VALUES ARE PERCENTAGE OF WEAR.

Material.	Standard Cylinder.		Slotted Cylinder.	
	Without Abrasive Charge.	With Abrasive Charge.	Without Abrasive Charge.	With Abrasive Charge.
Cherty limestone	3.6	4.8	11.0	11.8
Blast furnace slag, porous texture	16.6	18.0	29.8	40.8
Blast furnace slag, dense	6.8	7.8	16.8	18.0
Porous and dense slag mixed in equal parts	16.7	21.0	23.6	33.0
Blast furnace slag, densest variety	5.6	6.0	9.0	10.2

The machine used by the writer is mounted on the shaft at an angle of 30 deg.,—the same as in the standard,—while that

Mr. Mattimore. described by Mr. Scofield is horizontal. It is probable, therefore, that the two machines will give different percentages of wear for the same material, due to the different motions of the material during the test; but the main purpose of eliminating the dust cushion is accomplished in each.

In the machine used by the writer, as illustrated in Fig. 1, one guide on the frame at the cover end of the cylinder has been removed, which makes it practicable to charge and discharge the cylinder without removing it from the frame on the shaft. The cylinder thus attached is absolutely stable and has been run in this way continuously for three or four years.

No attempt has been made by the writer to accelerate the test, but as a time saver it is certainly worthy of investigation.

TRANSVERSE TESTING UNDER NON-UNIFORMLY DISTRIBUTED LOAD WITH SPECIAL APPLICATION TO AIRPLANE WING RIBS.

By Irving H. Cowdrey.

SUMMARY.

The construction of the airplane wing rib is such that the question of stress distribution through the various parts does not readily lend itself to solution by direct calculation. Hence the determination of the relative excellence of various designs becomes very largely a problem for laboratory solution. A laboratory test is of value directly proportionate to the accuracy with which the actual conditions of service are reproduced.

The actual load borne by each individual rib is distributed non-uniformly over the length. The rib itself is a member of astonishing lightness and frailty.

These conditions make the proper testing of such ribs a problem of considerable scientific and technical interest.

The method devised to meet the exigencies of the situation as described in the accompanying paper makes use of rubber bands of uniform characteristics and different widths to apply, at a large number of points, forces which shall closely approximate the conditions resulting from a non-uniformly distributed load. The method makes the determination of the distortion of the rib under load a matter of no great difficulty.

Certain check investigations have proved that the forces thus applied agree satisfactorily with those necessary to reproduce the conditions of load under service.

The approximation of uniformly or non-uniformly distributed load by this method would seem to have a reasonably wide application to other laboratory problems.

TRANSVERSE TESTING UNDER NON-UNIFORMLY DISTRIBUTED LOAD WITH SPECIAL APPLICATION TO AIRPLANE WING RIBS.

By Irving H. Cowdrey.

Introduction.

The work of the testing engineer is very largely that of qualitative determinations. A glance through the standards formulated and adopted by this Society will bear out this statement to the fullest. While it is true that certain specific methods of test have been devised and standardized with an attempt at reproducing in the laboratory the conditions existing in practice, these instances are comparatively rare.

That tests are continually made on specimens which in no wise resemble the form or size of the members appearing in the finished structure is not to be offered as an argument in any sense derogatory to the value of the results obtained. Whenever the structure is of such form and the loads of such a nature that the stresses in each member are determinate, specimens of the usual laboratory form may, with all propriety, be tested and the results used to determine the fitness of the material under consideration for the purpose intended.

There are, however, many types of structures in which the stress distribution between the various members and parts is very difficult or impossible to determine with the present engineering knowledge. Again, even though the load applied to the individual member may be known with a fair degree of accuracy, it is possible that the form or construction of the member itself may be such that the variation of stress through its different parts may not yield itself to the usual methods of calculation.

To this latter class belong many of the members entering into the construction of the frame of the airplane. Many experiments have been made to determine the forces acting on its aerofoils and other surfaces. Hence if the craft or any of its parts could be considered as a body of even approximate rigidity the stresses set up in most of its members could be calculated with some degree of precision. Morever, if its parts were fabricated from a material that obeyed perfectly the laws of elasticity and whose modulus of elasticity was known and constant, the stresses could be determined according to the methods common to the theory of elasticity. Such is, however, not the case. The structure is largely of wood, selected and seasoned it is true, yet possessing much of the variability of this material. Again the fittings, and types of attachment, the stays and adjusting devices are all of such a nature that exact calculations are difficult if not impossible. The secondary stresses induced in such a frame are a matter of very doubtful speculation.

This condition has lead to some attempts to test certain of the completed portions of the craft. The results have doubtless been instructive in some instances, but the writer feels that many of the tests made prior to the last year have been of very doubtful value. About a year ago it was suggested to the writer by Mr. Alexander Klemin, now connected with the U. S. Signal Corps, that some tests should be made to determine the relative values of certain methods of airplane wing rib construction. The problem seemed of such scientific, engineering, and timely interest that the matter was taken under careful consideration. In the development of the method described later in this paper, much very valuable assistance was rendered by Prof. Harrison W. Hayward and Mr. Ralph G. Adams, colleagues of the writer in the Testing Materials Laboratory of the Massachusetts Institute of Technology, where the tests were conducted.

Such tests as had been made up to that time, so far as the writer and his colleagues were aware, had been quite absurd. A few futile attempts had been made to obtain the strength of ribs by supporting at two points and loading with a single central load. The absurdity of such tests must be perfectly apparent to anyone familiar with airplane construction and the type of load to which these ribs are subjected. In any test it must ever be kept clearly in mind that the value of the results depends not only upon accuracy of observations, but equally upon the ability of the experimenter to reproduce in the laboratory conditions which are, as nearly as may be, identical with those to which the member under investigation will be subjected in practice.

THE PROBLEM.

The acceptance of the above premise necessitates, before all, the consideration of the manner in which the member is attached to the remainder of the wing frame, and the determination of the actual distribution of load to which it is subjected during flight.

The member itself is of great frailty, a rib five feet long weighing but nine ounces. This at the start introduces an element of somewhat unpleasant complication. To apply to such a member, whose transverse dimension is about one-half inch, a load which shall approximate in any degree that produced by wind pressure against a canvas covering offers some very interesting problems. Moreover this load is not only distributed, but distributed non-uniformly. The problem to be solved seemed after some consideration to divide itself into the following heads which will appear in the same order in the subsequent discussion:

1. Methods of support or suspension;
2. The distribution of load;
3. Application of load with the proper distribution;
4. Accurate measure of the load; and
5. Determination of the distortion of the member under test.

1. *The Method of Support or Suspension.*—In the completed wing, the ribs are connected by one or more continuous spars, passing from tip to tip of the wing. This affords secure lateral fastening at these points. To duplicate such a condition, the ribs were cut from a group or so fabricated as to leave in place a piece of spar about one inch thick.

This spar section may be seen at *A*, Fig. 2. In the cases furnishing data for this paper the two-spar suspension was used. To each of these spar sections was fastened a pair of steel plates $\frac{1}{8}$ in. thick, each plate having in its center a $\frac{3}{8}$-in. hole. The fastening was accomplished by means of four $\frac{1}{8}$-in. steel studs having a nut on each end. These studs appear at *A*, Fig. 3, and the hole for one of them may be seen at *1*, Fig. 2. With these plates in place a $\frac{5}{16}$-in. hole was bored through the wood to line as nearly as possible with the $\frac{3}{8}$-in. hole in the steel (see *2*, Fig. 2). The holes in the wood were then reamed so that a $\frac{3}{8}$-in. bolt with a finished shank could be just forced through by hand pressure. These $\frac{3}{8}$-in. bolts served then as the points of suspension and from them straps (*B*, Fig. 3) were carried to the maple plank *C*, Fig. 3, which in turn was suspended from a pair of chain falls. The suspension bolts were set up as tightly as possible without producing clamping action between the suspension straps and the side plates on the rib. This was to afford as much lateral support as possible without interference with freedom of vertical deflection under load.[1]

2. *The Distribution of Load.*—The very nature of the purpose of the airplane wings indicates a distributed load. The exact distribution was not investigated by the writer. Many experiments have been carried out to determine the intensity of pressure on the various parts of aerofoils under flying conditions. It is not the purpose of this discussion to comment upon the results that have been thus obtained. It is assumed that the diagram for the distribution of load on a rib is such as is indicated in the work by G. Eiffel, entitled, "La Résistance de l'Air et L'Aviation," and reproduced in the translation of the above by J. C. Hunsacker. These load diagrams show that the distribution varies under the varying conditions of flight, both in general outline and in the position of maximum intensity. Under such circumstances a representative load diagram must be arbitrarily chosen. For the purpose of these tests it was assumed that a straight-line diagram would be a satisfactory approximation. Moreover, it was assumed that the point of maximum intensity could reasonably be assumed at a distance of one-fifth the chord length from the leading edge of the wing.[2] (Shaded area, Fig. 1.)

Such a distribution, as well as the general dimensions of the members, precluded the possibility of anything in the line of sand or hydraulic cushioning. Hence, a truly distributed load seemed impossible. With the member under test the total length was 60 in. A load, more or less concentrated, applied at each 4-in. interval giving 14 points of loading, could be presumed to give a fair approximation to the distributed load desired, provided these individual loads be properly proportioned.

---

[1] The method of suspension here used does not perfectly duplicate the supporting of the ribs in the frame of the wing. The attachment of the fuselage to the spars is such that twisting of the spar at these points is prevented to a large degree. Actual conditions would then, possibly, be more accurately reproduced if the straps *B*, Fig. 3, were clamped to the spar section in place of the intermediate side plates at *A*.

[2] Some tests have been made by various experimenters since those here described in which the point of maximum load intensity is further from the leading edge. In some of the design calculations this point is taken at mid-chord instead of as indicated above.

There have been some experiments made within a very few months in which but eight loading points have been used. To the writer this number seems entirely too small. The common methods of construction provide for the entire removal of the web of the rib at frequent intervals. A reference to Fig. 3 will show the extent of such removal in the type of rib under test. The portions of the rib over one of these spaces act like secondary beams under load. A number of loading points less than was used in the tests under consideration produces, in the writer's opinion, very serious effects on the stress distribution throughout the rib. It would seem that the number of loading points should be greater than those used in this case rather than less.

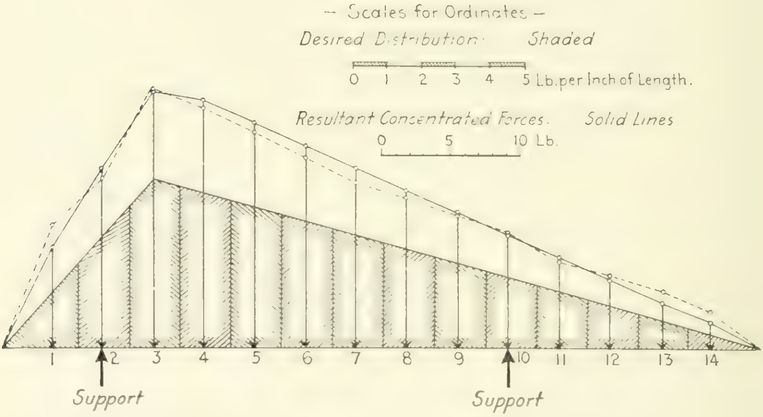

– Scales for Ordinates –
Desired Distribution Shaded
0 1 2 3 4 5 Lb. per Inch of Length.
Resultant Concentrated Forces. Solid Lines
0 5 10 Lb.
1
2
3
4
5
6
7
8
9
10
11
12
13
14
Support
Support

FIG. 1.—Force Distribution for 150 lb. Total Load.

Using the number of loads noted above the problem of proper proportionment was attacked as follows: The load diagram for a total load of 150 lb. is divided into 14 parts (see Fig. 1). The ends are triangles with bases each 6 in. long. The remaining divisions then take the form of trapezoids, with the exception of division 3. Each division has a 4-in. base. Each of these areas then represents the load distribution desired over a length bounded by its extreme ordinates. The computed resultant for each of these areas appears below:

LOAD NO.	LOAD, LB.	LOAD NO.	LOAD, LB.
1	7.5	8	11.7
2	13.3	9	10.0
3	19.0	10	8.3
4	18.3	11	6.7
5	16.7	12	5.0
6	15.0	13	3.3
7	13.3	14	1.9

The application of concentrated forces according to the above schedule then should give a loading quite comparable with that indicated by the straight-line diagram. Theoretically these fourteen concentrated forces should be applied at the centers of gravity of the respective areas. This has been done for numbers 1 and 14. In the other instances it has been assumed that the middle ordinate is sufficiently near to the center of gravity. This introduces an error of from 0.03 to 0.17 in. in the location of these resultants. In the case of the larger central forces this error in location is least. These resultant forces are shown as solid lines in Fig. 1. To aid in a comparison to be made later their ends having been joined by a solid line.

3. *The Application of Load with Proper Distribution.*—The problem now resolves itself into one of the simultaneous application of fourteen different loads. Not only must the application be simultaneous, but the rate of increase in the application of each load must be such that under any total load whatever the relation between the various forces must be the same as the relation shown in the above tabulation. If the problem were solely that of applying the loads without the complication of absolute adherence to the maintenance of this relation, the solution would be quite simple. The familiar expedient of pouring shot or sand into a bucket would suffice. But to make a device to deliver sand or shot simultaneously into a large number of buckets, and into each at a different and definitely

predetermined rate seems scarcely practicable. Again, if the number of loading points were made a power of two, and perhaps limited to eight in number, some modification of the scheme so commonly used in multiple-point loading of large beams could be arranged. This method is quite complicated with 8-point loading and becomes doubly complicated with 16-point loading, which is the next step in such a method. With all this in mind, careful consideration lead to a complete discard of all such methods and the final adaptation of what the writer believes to be a new departure in load application. It was felt that the most satisfactory solution of the problem could be reached by the application of load through a series of rubber bands of uniform properties whose widths should be made directly proportional to the load each band was expected to apply. These

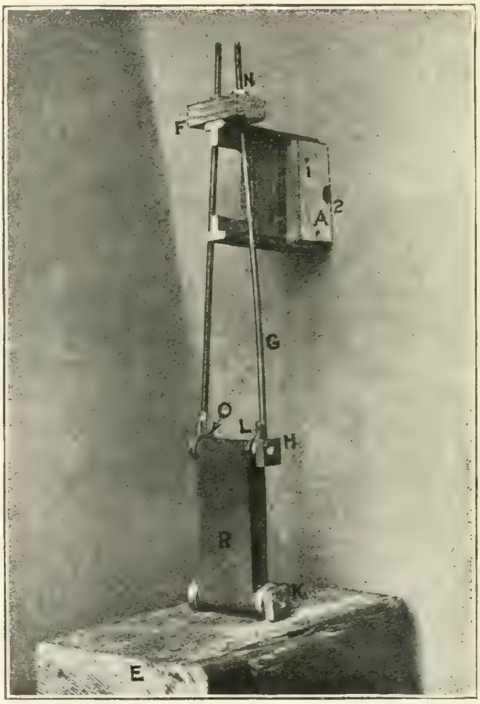


FIG. 2.—Detail of Loading Device.

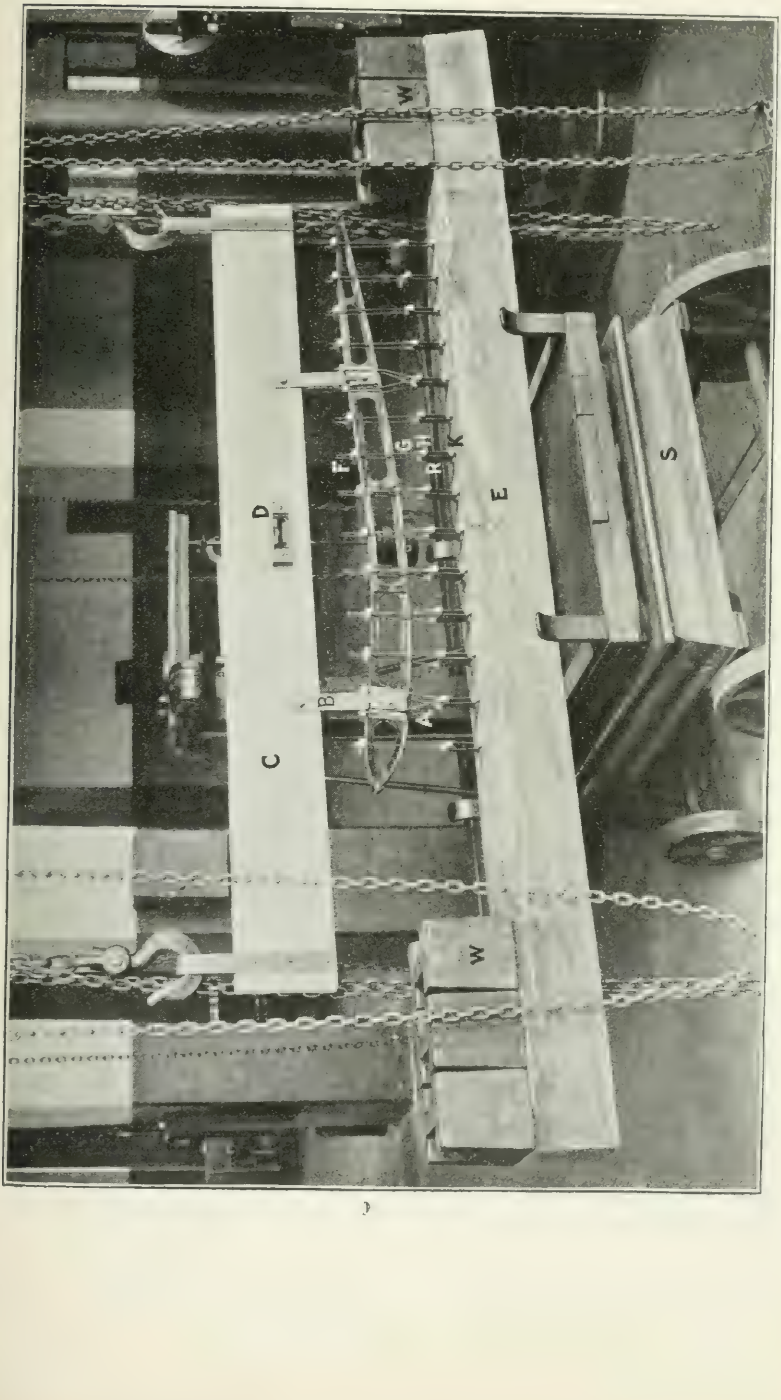


FIG. 3.—Apparatus for Testing Wing Rib, Non-Uniform Load Distribution.

bands were obtained by cutting sections from a motorcycle inner tube. The particular tube used was of red rubber for a 28 by 3-in. tire.

With such an ideal series of bands, let one end of each be fastened to a rigid support, such as *E*, Figs. 2 and 3, and the other properly attached to the rib under test. The suspension of the rib as already described will permit it to be raised while a level (*D*, Fig. 3) enables a proper horizontal alignment of the supports. Under such conditions, neglecting the deflection of the rib itself, the fourteen loads will be applied at the predetermined points and with exactly the predetermined distribution.

In the device as illustrated by Figs. 2 and 3 the attachment of the bands is as follows:

Into the timber *E* are screwed at *K* heavy screw eyes of a size proper to take a ¼-in. stove bolt. Each pair of eyes are so spaced transversely on the timber that they permit on the bolt, between their inside faces, a pair of washers between which is a thin brass tube of a length equal to the width of the rubber band, *R*, which is to be used at that particular loading point. This gives the rigid fastening for one end of the band. Two ⅛-in. hard brass wires, *G*, with a soldered eye (*L*, Fig. 2) in the lower end of each, *H*, and threaded at the upper end, pass through a small wooden block at *F*. On the upper side of *F* washers and nuts (*N*, Fig. 2) afford a ready means of adjustment of the length of this stirrup-shaped device. A stove bolt with tube and washers (*O*, Fig. 2) passes through the eyes of the wire rods. Such device affords a proper means of attachment between the upper end of the rubber band and the member under test. The proper adjustment of these stirrups will be discussed under "Notes, Suggestions and Precautions."

4. *Accurate Measurement of the Load.*—As will be readily seen from Fig. 3 the heavy timber *E* (in this particular test a 6 by 6-in. hard pine stick weighing about one hundred pounds) rests on platform scales, *S*. On each end of this timber are three 50-lb. weights *W*. With no tension in the bands *R*, the tare weight of the timber and weights is read on the scales. The plank *C* is raised and maintained level, thus stretching the bands and hence applying to the rib, loads according to the predetermined schedule. The summation of these fourteen

loads may be obtained at any instant by balancing the beam of the scales and noting the difference between the reading obtained and the original tare weight. The accuracy of this determination depends solely upon the accuracy of the scales. This should usually be within a half pound.

Scales of the ordinary platform type were used in this method of test for two reasons: First, in the opinion of the writer a greater precision can be thus obtained than with any of the forms of testing machines commonly employed in laboratory work; second, it was desired to produce a method of testing that could be carried out easily by the manufacturer and permit and encourage experimental work on rib design by those who are not privileged to have at their disposal a properly equipped laboratory.

5. *Determination of the Distortion of the Member under Test.*—It is believed that the actual strength of a wing rib is but a partial solution of the problem at hand. The writer would not pose as an expert in aerodynamics nor in airplane design, yet to any engineer of analytical turn of mind the question of the effect of wing distortion must present itself. If the wing surface changes appreciably under conditions of flight does it not seem possible that some of the expectations of the designer may fall far short of fulfillment? If the designer expects so much lift, so much drift, and such a center of pressure, what unexpected factor enters into the problem through the possibly unforseen distortion of his aerofoil?

The possible importance of rib distortion would seem to make such determination a requisite adjunct to any satisfactory method of test. However, in view of the fact that many variables in the line of material and workmanship enter into the fabrication of each rib, it would seem that undue precision in the distortion determination is neither necessary nor advisable. A precision of 0.01 in. is doubtless satisfactory and such precision is possible with the device under consideration.

Throughout this discussion it is assumed that any distortion of the timber *E* which may occur is of such magnitude as to be absolutely negligible. As the plank *C* is raised the rubber bands become elongated. This elongation is measured by means of dividers set in center punch marks in the ends of the stove bolts *H*, *K*, etc. If there were no distortion of the rib, the increment of length of all bands would be the same under any given total load. Such is found not to be the case. For the particular test under discussion, these increments of length for loads of 50, 100, 150 and 175 lb., respectively, will be found in Table I. In Fig. 4 these increments of length have been plotted from arbitrary reference lines not shown. Now points 2 and 10 are the points of suspension as well as loading points. Hence so far as the rib is concerned these are points of zero deflection.

In each curve of Fig. 4, straight lines have been passed through the intersections of the curve with these two ordinates. Such lines serve then as lines of reference from which the actual distortion of any part of the rib may be determined for the particular load in question. The distortion curves are drawn showing the rib in its true position in flight. It will be noted that with the load distribution assumed, the particular rib under investigation showed a noticeable droop of the leading edge with a corresponding up-tilting of the trailing edge. Whether this distortion is of a magnitude and nature to affect the aerodynamics of the craft in flight is not within the province of this discussion.

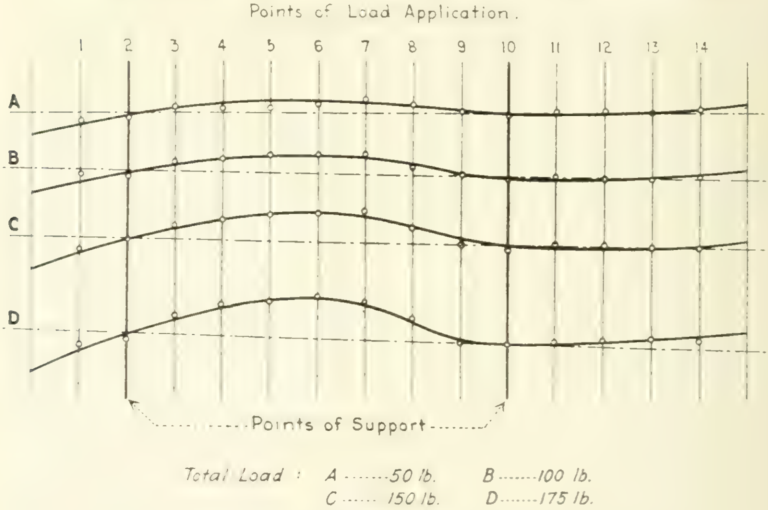


Fig. 4.—Distortion of Rib. Ordinates equal Distortion with respect to a Datum Line through Points of Support; Ordinates Full Size.

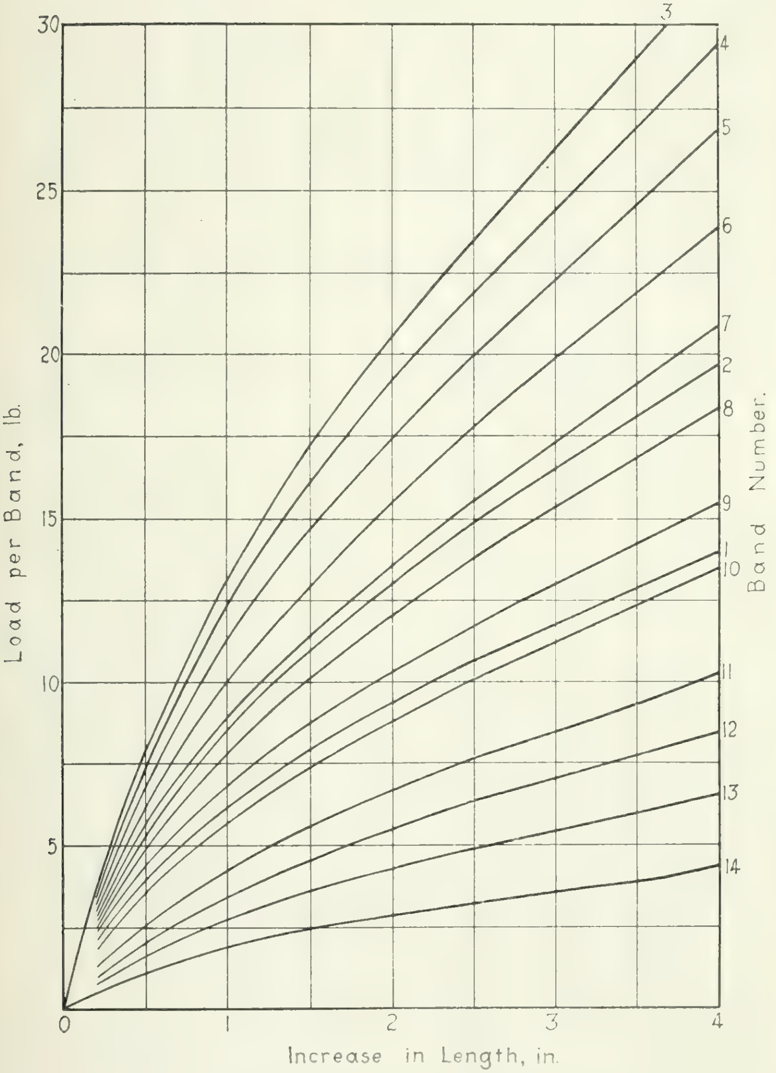


FIG. 5.—Calibration Curves for Rubber Bands.

In the interpretation of these curves it must be borne in mind that while the ordinates are plotted full size, the chord length of the rib is vastly contracted.

Checking the Load Distribution.—While there was every reason to believe that the method of loading described in the previous pages would yield a load distribution quite closely in accord with that indicated by the diagrams of Fig. 1, still it seemed desirable to check the loads as carefully as might be. Such a check investigation is described in the following text.

Each band, after being cut to the proper width, was calibrated to determine the load-elongation relation through and somewhat beyond the range expected to be used in the rib test. These calibration curves appear in Fig. 5. For convenience in use, the increment in length has been plotted as abscissa rather than the actual length of the band. It should be noted, however, that the original length of the bands varied not over 0.02 in. The "band number" refers to the position of the band in question in the loading scheme (see Figs. 1 and 4). During the test, as has been previously noted, readings were made so that the increment in length is known for each band at each of the four specific loads investigated.

This increment, by reference to the calibration curves of Fig. 5, makes it possible to determine the force applied at *each* of the fourteen loading points. For any given set of readings, the sums of the individual forces thus determined should, of course, check with the summation as indicated by the reading of the scale beam. The closeness of this check between the apparent and actual summation is indicated in Table I. With the exception of the 50-lb. load investigation the discrepancies average about 1 per cent. It is only to be expected that the discrepancy for very small loads will be large due to the difficulty in making accurate interpolations on the calibration curves.

A detailed comparison has also been made between the computed and applied forces for a total load of 150 lb. Such comparison is shown graphically in Fig. 1. The forces as determined by the calibration curves have been plotted in the figure and the ends of ordinates thus obtained are joined by the dotted line. The closeness with which this follows the solid line joining the ends of the ordinates representing the

TABLE I.—DETAILED LOAD INVESTIGATION.

Band No.	Initial Reading, in.	Load by Scales, 50 lb.			Load by Scales, 100 lb.			Load by Scales, 150 lb.			Load by Scales, 175 lb.			Band No.
		Length, in.	Increase in Length, in.	Force from Curves, lb.	Length, in.	Increase in Length, in.	Force from Curves, lb.	Length, in.	Increase in Length, in.	Force from Curves, in.	Length, in.	Increase in Length, in.	Force from Curves, lb.	
1	2.47	2.87	0.40	3.4	3.45	0.98	6.2	4.36	1.89	9.1	4.96	2.49	10.7	1
2	2.50	2.88	0.38	4.4	3.50	1.00	8.7	4.34	1.84	12.5	4.96	2.46	14.7	2
3	2.47	2.80	0.33	5.7	3.39	0.92	12.5	4.23	1.76	19.1	4.81	2.34	22.7	3
4	2.47	2.80	0.33	5.2	3.37	0.90	11.5	4.20	1.73	17.7	4.75	2.28	20.7	4
5	2.47	2.80	0.33	4.8	3.35	0.88	10.4	4.17	1.70	15.9	4.73	2.26	18.8	5
6	2.53	2.84	0.31	4.1	3.41	0.88	9.3	4.22	1.69	13.9	4.76	2.23	17.5	6
7	2.54	2.82	0.28	3.7	3.41	0.87	8.1	4.21	1.67	12.2	4.79	2.25	14.6	7
8	2.53	2.84	0.31	3.5	3.46	0.93	7.6	4.29	1.76	11.1	4.87	2.34	13.2	8
9	2.52	2.86	0.34	3.3	3.50	0.98	6.8	4.37	1.85	9.8	4.98	2.46	11.7	9
10	2.52	2.88	0.36	2.9	3.52	1.00	5.7	4.40	1.88	8.5	4.99	2.47	10.0	10
11	2.53	2.87	0.34	1.9	3.51	0.98	4.3	4.37	1.84	6.4	4.99	2.46	7.6	11
12	2.55	2.89	0.34	1.5	3.55	1.00	3.5	4.40	1.85	5.3	5.00	2.45	6.3	12
13	2.58	2.93	0.35	1.3	3.58	1.00	2.7	4.44	1.86	4.1	5.03	2.45	4.8	13
14	2.52	2.85	0.33	0.7	3.51	0.99	1.9	4.38	1.86	2.7	4.96	2.44	3.2	14
			Sum	46.4			99.2			148.3			176.5	
			Discrepancy	−7.2%			− 0.8%			− 1.1%			+ 0.9%	

desired forces would indicate that the method which has been herein discussed should prove satisfactory for this type of investigation.

NOTES, SUGGESTIONS AND PRECAUTIONS.

Preliminary Adjustment of Stirrups.—It is necessary to make a very careful adjustment of each stirrup before attaching the rubber bands, in order that when the plank and rib are raised for the application of load, each band shall start elongating at the same instant. The most satisfactory of the methods tried is as follows: Lower the rib until the lowest point of the bottom edge will clear the timber *E*, Fig. 2, by some convenient amount. A single bolt should now be passed through the eyes in the timber *E* and through the eyes of the corresponding stirrup. By means of the adjusting nuts *F*, the stirrup may be brought to the proper length. When each stirrup has been thus adjusted, the level *D* should be set by means of the slotted end fastenings, so that the bubble will be in the center of the glass.

With all the above precautions observed, the stirrups may be released from their companion eyes, the rib and attachments raised and the rubber bands put in place.

The Rubber Bands.—The tube from which these bands were cut was of uniform thickness throughout. This uniformity is very convenient since less care is necessary in adjusting the bands than would be requisite if the thickness varied as is the case with some types of tubes. It is believed that in cutting bands from a tube, as was done in this investigation, the width may be obtained accurately to about 0.01 in. In choosing the scale of width there are two antagonistic conditions to be considered:

1. It is desirable that the length increment of the band under load should be large compared with the deflection of the member under test so as to minimize the error in loading due to the variation in length increment of the various bands.

2. The maximum load applied by any band should probably not exceed one-fifth the strength of the band. This would be somewhat dependent upon the quality and resiliency of the material used.

The bands used in this test were of material showing a strength of about 125 lb. per inch of width when tested as a band. The elongation at fracture was about 1000 per cent.

It would seem feasible to substitute for bands cut to a predetermined width as in this case, some of the better grades of para rubber bands, which may be purchased in definite sizes. Combinations of such bands could be used in parallel and tested by calibration, so as to obtain the desired force at each point of loading.

TABLE II.—CALIBRATION OF RUBBER BANDS.

Band No.	Length Increment, in.	Load, lb.		Variation, lb.
		October.	April.	
1........	1	6.1	6.3	+0.2
	2	9.3	9.4	+0.1
	3	11.8	12.0	+0.2
	4	14.1	14.6	+0.5
				Aver....+0.25
3........	1	13.1	13.6	+0.5
	2	20.6	20.8	+0.2
	3	26.3	26.6	+0.3
	4	31.6	32.2	+0.6
				Aver....+0.40
5........	1	11.4	11.5	+0.1
	2	17.4	17.4	0.0
	3	22.0	22.2	+0.2
	4	26.9	27.1	+0.2
				Aver....+0.13
7........	1	8.8	8.8	0.0
	2	13.4	13.4	0.0
	3	17.1	17.2	+0.1
	4	20.8	21.0	+0.2
				Aver....+0.08
9........	1	6.7	6.5	−0.2
	2	10.1	9.9	−0.2
	3	12.9	12.8	−0.1
	4	15.6	15.6	0.0
				Aver....−0.13
11........	1	4.3	4.4	+0.1
	2	6.8	6.6	−0.2
	3	8.4	8.5	+0.1
	4	10.3	10.2	−0.1
				Aver....−0.03
13........	1	2.9	2.7	−0.2
	2	4.3	4.3	0.0
	3	5.4	5.5	+0.1
	4	6.7	6.6	+0.1
				Aver.... 0.00

For the highest refinement it might be desirable to calibrate the bands, allow a period of rest, make the test and recalibrate after a second period of rest, using as a calibration curve the mean of the first and last determinations. In the opinion of the writer this double calibration should not be necessary. In order to justify this belief and to determine whether or not any appreciable change may be expected in the characteristics of the rubber bands within a reasonable time, a second calibration was made on half the bands six months[1] after the calibration made to determine the curves of Fig. 5. The data for the original and secondary calibrations appear in Table II.

In the analysis of this table three things must be borne in mind:

1. The data were intended to serve as a basis for plots. In drawing the representative curves the slight variations will not appear, hence the algebraic sign of the variations has been recognized in computing averages.

2. The elongations may be in error ± 0.01 in.

3. The testing machine used has a precision of probably no better than ±0.1 lb. within the range of load used.

When these last two items are taken into consideration it is very evident from an examination of the averages that the variations are negligible in all the bands quoted except perhaps band No. 3.

If the variation in the properties of the bands during a six months' period are negligible the short time variation need be given no great consideration.

Lateral Support.—The rib pictured in Fig. 3 was tested to destruction with the apparatus as shown. It is true that these ribs receive certain lateral support at one or more intermediate points by means of the stringers. If it is desired to apply such support, there are several ways by means of which this may be accomplished. Three of these will be enumerated below.

1. To the plank *C*, Fig. 3, there may be fastened side pieces of white oak. These should be made with a typical "buck-stave" contour and held rigidly by through bolts. They should extend well below the lower edge of the rib. The inside faces should be polished with oil and be slightly lubricated before the test. They should be made and adjusted, by shims if necessary, so that a clearance of about 0.01 in. is present between them and the rib.

---

[1] The first calibration was made in October, 1917, and the second in April, 1918.

2. This type of support may be modified by using the "wooden buck staves" so separated that a yoke furnished with end rollers may be fastened to the rib at the upper and lower edges, and so adjusted that these rollers shall bear on the supports.

3. Some type of straight-line motion may be used. The supporting frame for this linkage may be fastened to the plank *C*.

In the opinion of the writer the type of lateral support first described should prove satisfactory.

Distortion Readings.—It has been previously stated that the curves of Fig. 4 give an indication of the distortion of the rib. This is open to a slight objection, at least with the type of rib illustrated by Fig. 3. Several of the loads are applied at points beneath which the web has been largely cut away. At these points there enters a disturbing secondary beam action superposed upon the distortion of the rib as a whole. No attempt has been made to correct for this effect.

Correction for Deflection of the Rib.—With the calibration curves at hand it is possible by means of the nuts at *N*, Fig. 2, to adjust the length of the stirrups during the test so that the load actually applied is exactly equivalent to that computed in the preliminary calculations according to the method shown by Fig. 1.

Extension of the Principles Involved.—While this method of testing was developed to meet the exigencies arising in the testing of aircraft wing ribs, it is felt that it possesses the possibility of wide application. A number of ribs may be tested as a unit with any system of loading which experimental evidence or theoretical aerodynamics may suggest. A spar, a wing section, or any portion of the frame or of the completed craft may be loaded and the behavior of that portion may be investigated. The magnitude of the forces involved may be many times greater than those arising in the test herein described. Rubber tubing may be readily obtained which will yield bands showing a strength of 400 lb. per inch of width. Using bands of this type 6 in. wide will permit the application of forces of 500 lb. each. With such forces spaced 2 in. apart, loads of 3000 lb. per lineal foot are possible. Under loads of such magnitude a very massive member must be used to replace the member *E*, Fig. 2. It would also seem possible to conduct tests in which the forces shall not be confined to a single plane. The chief difficulty to be surmounted would be that of constructing a suitable supporting frame to afford points of attachment for the various devices which would be found necessary in the application of the desired loads

A SIMPLE TYPE OF BRINELL TESTING MACHINE FOR 500 KG. LOAD.

By A. V. de Forest.

SUMMARY.

This paper describes a simple type of Brinell testing machine for 500 kg. load.

A series of measurements with five different machines shows the errors involved in this test on annealed brass, and the simple type of machine is proved to be satisfactory.

Some suggestions are made as to the possibility of obtaining speed and accuracy with this method of hardness determination.

A SIMPLE TYPE OF BRINELL TESTING MACHINE FOR 500 KG. LOAD.

By A. V. de Forest.

A Brinell testing machine was recently devised for use on cartridge brass, which was so successful that a description may be of interest to others.

Description of Machine.

The first machine built, which is illustrated in Fig. 1, was simply a yoke weighted to 500 kg., carrying the test ball, and an automobile jack arranged to lift the yoke with the specimen between jack and ball. The yoke had to be stayed in order to prevent its creeping along the bench on which the jack rested. In order to prevent any side thrust distorting the shape of the hole, as the load was released, a flexible member, allowing only vertical motion, was put in between the jack and the yoke.

This crude arrangement was so satisfactory that a better machine, illustrated in Figs. 2 and 3, was designed on the same principle. An old iron stand from the junk heap was used, and a vertical shaft, lifted by a threaded bevel gear, took the place of the jack. This shaft is fitted to a bearing at the bottom, and moves freely and smoothly. The hand wheel gives a motion of 0.01 in. per revolution, and requires about four turns to produce the impression. The motion is continuous, and the rate of application of load can be kept fairly uniform.

This machine is easily arranged to test two specimens at once, by placing the ball in a flexible holder between the two specimens, as shown in Fig. 3. To make this test a little handier, a spiral spring was introduced between the anvil and vertical shaft. This holds the two specimens until the load is applied, and prevents their falling when released.

Comparison of Five Brinell Machines.

A comparison of this type of machine with the regular hydraulic instrument was undertaken to try to determine whether the considerable hardness variation between different parts of the same specimen was due to the test or to actual differences in the metal. A sheet of hard-rolled cartridge brass, about 2 ft. long and $4\frac{3}{4}$ in. wide, by 0.150 in. thick, was annealed in a gas muffle with one end projecting from the furnace in order to produce a somewhat uniformly varying anneal from end to end. Five rows of Brinell impressions, $\frac{1}{2}$ in. apart, were then made as shown in Fig. 4. Five machines were used, so that the sequence was repeated every $2\frac{1}{2}$ in. Each longitudinal line began $\frac{1}{4}$ in. ahead of the preceding one, so that any regular change in hardness, either lengthwise or across, would not introduce errors. The five machines used were as follows:

No. 1....Olsen Hydraulic;
No. 2....Original Dead-Weight Type;
No. 3....Actiebolaget Alpha;
No. 4....Actiebolaget Alpha;
No. 5....New Dead-Weight Type.

In addition to the impressions on the five longitudinal lines, impressions were taken with machine No. 5 on a sixth line, as illustrated in Fig. 4.

Two diameters of each impression, at right angles to each other, were read with a filar eyepiece micrometer used in one tube of a binocular microscope of unusually large field. These were recorded separately, averaged, and the Brinell numbers read from a large scale plot. The magnification was not adjusted to read directly in millimeters, but a standard scale, ruled on glass, was measured many times and an average taken. This factor was incorporated in the plot. These readings were accurate to about 0.5 per cent.

Fig. 5 gives the Brinell hardness number of each impression in order. A fair curve was then drawn as close to an average value as possible. Readings consistently higher or lower than the curve show purely constant errors, either inaccurate load, friction in the hydraulic machines, or possibly error in the ball diameter. A factor can take care of this type of error.

The more serious errors are shown by irregularity in position with reference to the assumed mean. This can only be explained by irregular action of the testing machine, or extremely local variation in the brass. As some machines are consistently more regular than others, the trouble is presumably with the machine. The load was applied with care and regularity in every case but one. Machine No. 1, Group C, was accidentally overloaded, and gave a grossly erroneous result.

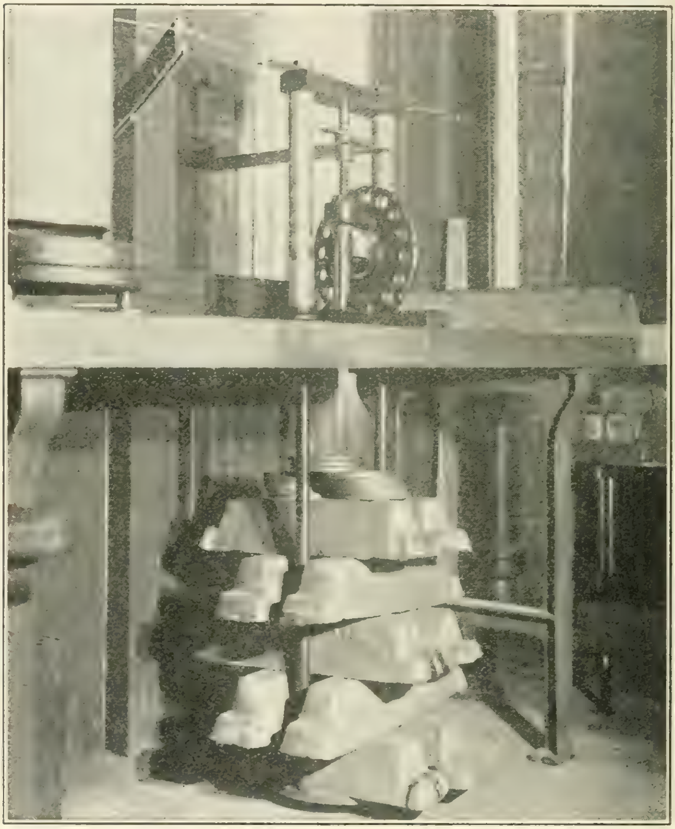


Fig. 1.—Original Dead-Weight Type of Testing Machine.

Another method of estimating the machine variation is by plotting the five neighboring indentations made by the same machine, which has been done in Fig. 6. These impressions are in a straight line, and slightly more than $\frac{1}{2}$ in. apart (see

Fig. 4). They should not show any greater variation in one machine than in another, but an inspection of Fig. 6 gives the same result, as to order of merit, as indicated by Fig. 5. The straight lines represent the mean of the five measurements, and allow an estimate of the variation encountered.

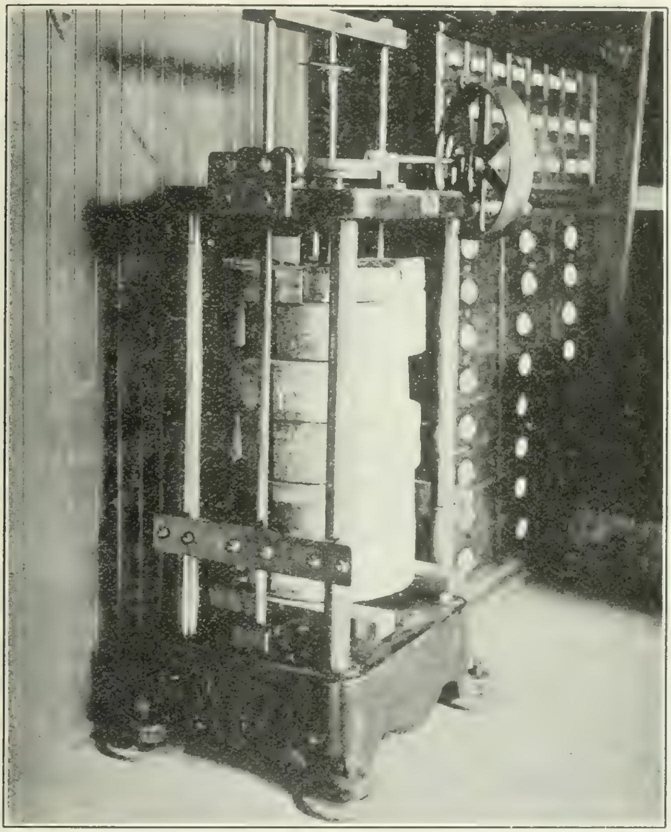


FIG. 2.—Improved Brinell Testing Machine for 500 kg. Load.

The irregularities, in relation to the assumed mean, as measured from Fig. 5, are given below. The figures represent the average of the maximum variations from the assumed mean curves in each of the nine groups made by each machine. Consistent variations are therefore excluded.

MACHINE.	AVERAGE MAXIMUM VARIATION.
No. 1	2.25
No. 2	1.32
No. 3	1.26
No. 4	1.27
No. 5	1.06

The order of merit of the machines, as indicated by the results obtained from this series of tests, is therefore 5, 3, 4, 2, 1.

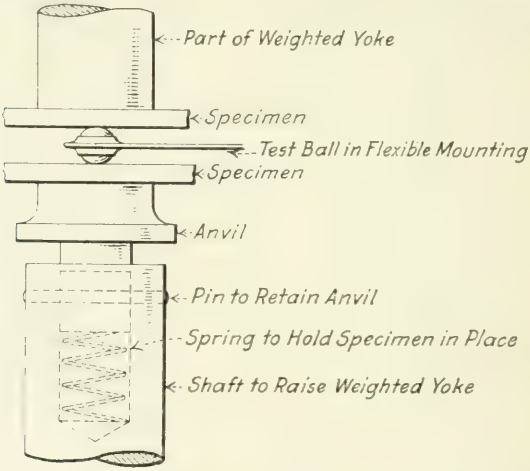

Part of Weighted Yoke
Specimen
Test Ball in Flexible Mounting
Specimen
Anvil
Pin to Retain Anvil
Spring to Hold Specimen in Place
Shaft to Raise Weighted Yoke

FIG. 3.—Arrangement for Testing Two Specimens at Once.

Machine No. 3 is consistently higher than the mean by about 1.8 Brinell numbers. Machine No. 4 is usually low in Brinell number. This instrument has been used on hardened steel, and the ball was somewhat out of round, the two diameters of the impression differing consistently by about the same amount.

The curve plotted from machine No. 5 only, gives an idea of the variation to be expected in carefully annealed stock. The maximum deviation is about one Brinell hardness number. In view of the good record of this machine, as indicated in Fig. 6, showing the relation of adjacent indentations, it is difficult to explain these comparatively large variations as due to mechanical error.

Features Concerning Speed and Accuracy of Testing.

The measurement of the Brinell impression is rather unsatisfactory if strict accuracy is required. The ordinary measuring microscope, with a fixed millimeter scale in the eyepiece, is of too low a power (10 diameters) for great accuracy, and the diffuse illumination makes a polished surface almost necessary. Fortunately, this can be done after the impression is made, by rubbing the spot with the finger or with a pencil eraser. A very slight film of prussian-blue pigment, as used when scraping in bearings, will give a good margin to the hole. The blue is squeezed out of the depression and, if of the right consistency, leaves a dark ring at the exact edge of the indentation. A little greasy dirt on the surface often gives the same effect. The filar eyepiece micrometer, used in a prism binocular with a 55-mm. objective, gives about 22 diameters magnification, and a flat field of 5 mm. The illumination here used is a microscope lamp with a 100-watt concentrated filament lamp with "daylight" ray filter and condenser. The illumination is at an angle of about 30 deg. to the surface of the metal. This gives a good margin at the edge of the depression opposite the light, and an unpolished piece gives a fair margin at the opposite edge. A polished specimen gives a good reading at the edge toward the light, if a piece of card-board or even the finger nail be used as a reflector to illuminate the depression, and leave the surface

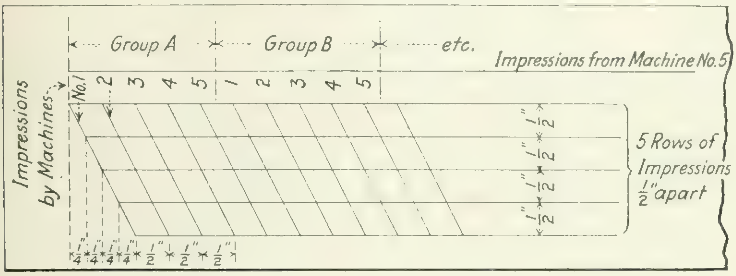
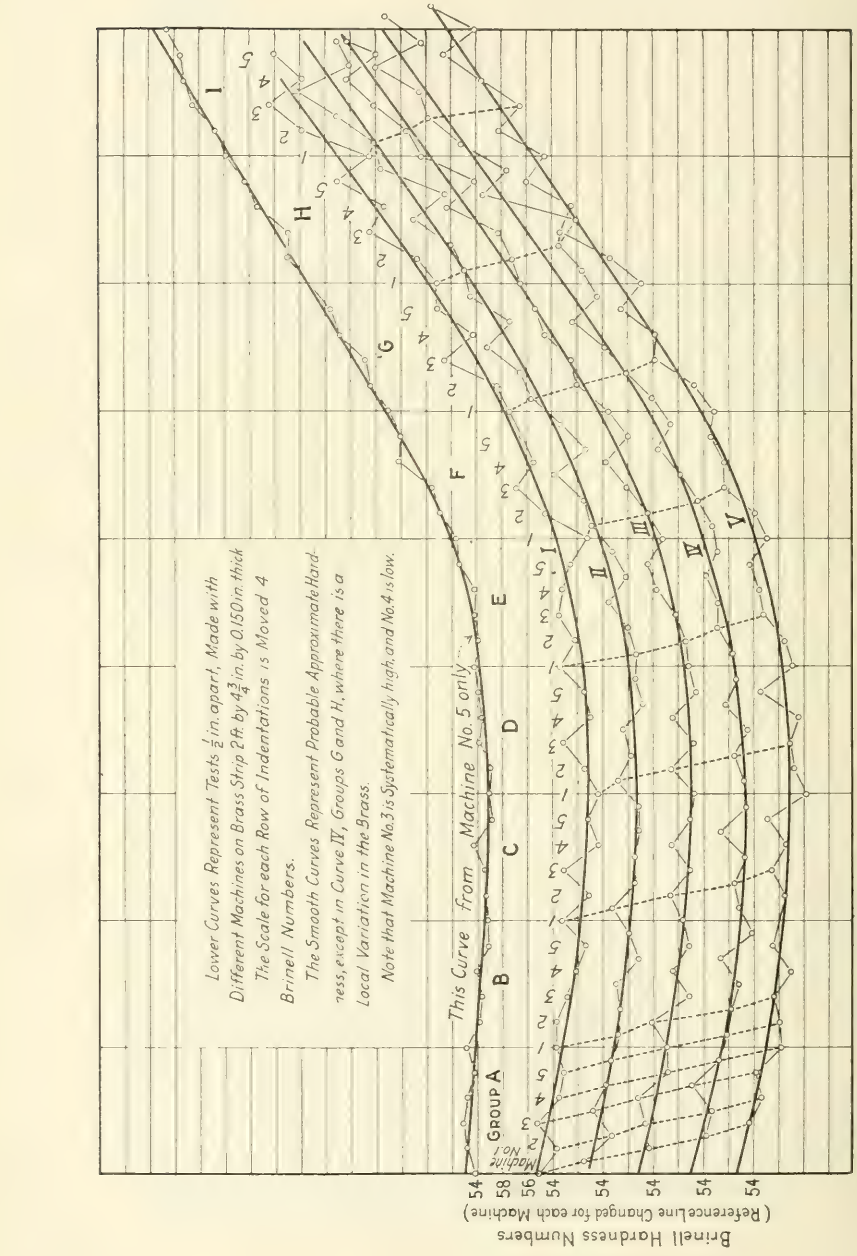


FIG. 4.—Location of Impressions on Brass Sheet.

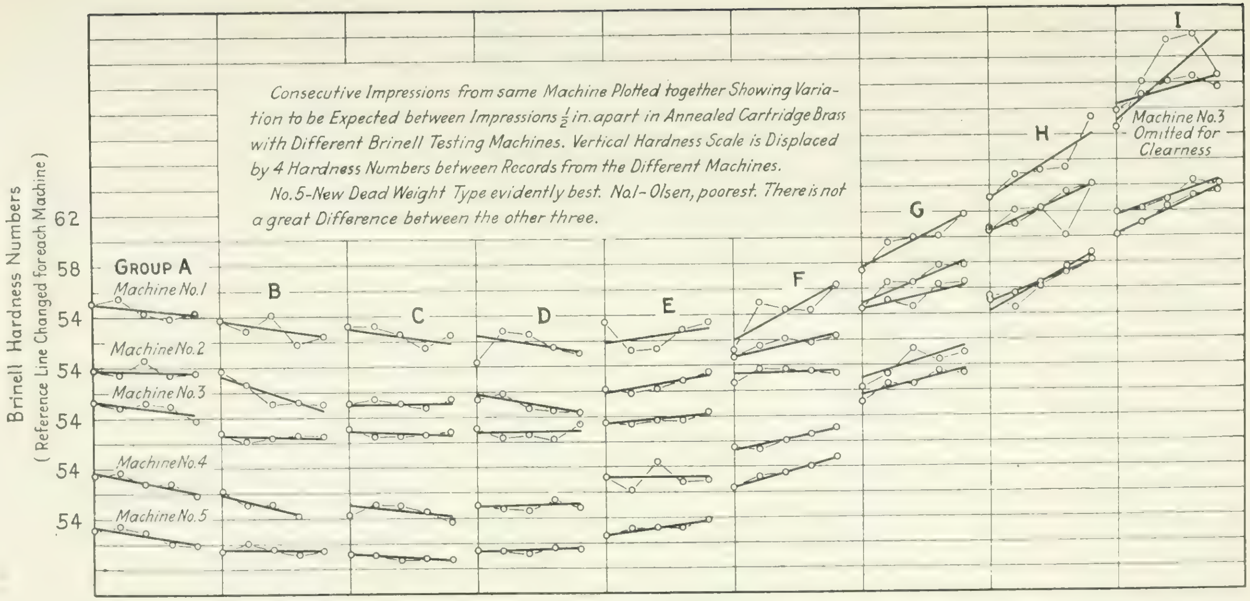


Lower Curves Represent Tests $\frac{1}{2}$ in. apart, Made with Different Machines on Brass Strip 2 ft. by $4\frac{3}{4}$ in. by 0.150 in. thick. The Scale for each Row of Indentations is Moved 4 Brinell Numbers.

The Smooth Curves Represent Probable Approximate Hardness, except in Curve IV, Groups G and H, where there is a Local Variation in the Brass.

Note that Machine No. 3 is Systematically high, and No. 4 is low.

FIG. 5.—Test Results: Impressions from the Five Machines Plotted in the Positions and Sequence indicated in Fig. 4.



Consecutive Impressions from same Machine Plotted together Showing Variation to be Expected between Impressions $\frac{1}{2}$ in. apart in Annealed Cartridge Brass with Different Brinell Testing Machines. Vertical Hardness Scale is Displaced by 4 Hardness Numbers between Records from the Different Machines.

No. 5-New Dead Weight Type evidently best. No. 1-Olsen, poorest. There is not a great Difference between the other three.

Machine No. 3 Omitted for Clearness

FIG. 6.—Test Results: Consecutive Impressions from the Same Machine Plotted Together.

dark. Where still more accurate measurement is needed, the depression may be photographed with a scale ruled on glass over the hole, with the graduated side on the surface of the metal; or this arrangement of glass scale can be used at a magnification of about 100 and the extremities of the diameters estimated or measured from the nearest graduation on the glass. A true measuring microscope is, of course, more convenient than any of these methods. Where two diameters are wanted on every reading, an eyepiece micrometer, ruled in squares as used for blood count, is very convenient.

An attempt was made to build a direct-reading depth gage on the Brinell machine. A small steel washer, with three short feet, was placed under the ball, the three feet allowing firm contact with the surface in spite of small irregularities. This was loosely attached to two rods moving freely through holes on each side of the ball, and connected above the yoke bar so as to allow individual motion. The relative movement of the ball and the metal surface under test was measured by a telescope and system of mirrors, giving a deflection of about 8 cm. for a depth of impression of 0.3 mm. The results were not wholly dependable, but gave some insight as to the creep after full load was applied, and showed up a possible source of error. So far as brass is concerned, there seems to be no creep after the first two seconds from the time full load is reached. This is borne out by the general observation that no change can be observed by prolonging the time under test.

Another effect found with this device is that interrupted loading near the total load may cause serious variation. If the depth is, say, 0.300 mm. at full load continuously applied, and another test on the same piece, close to the first, is interrupted for a few seconds at a depth of perhaps 0.290 mm., the metal will, as it were, "freeze" at that depth and not give the proper full size of impression. The corresponding hardness numbers are 53.0 and 54.9. A machine which applies the load continuously is, therefore, best; or at least the pressure should not be interrupted close to the final amount in those instruments having a reciprocating pump. This effect is illustrated in a different way in my paper on "Some Experiments on the Plastic Elongation of Wire" presented before this Society in 1916.[1]

---

[1] *Proceedings*, Am. Soc. Test. Mats., Vol. XVI, Part II, p. 455 (1916).

There, the self-hardening under tension is shown even where the load is continuously applied. Nearly any tension test of brass, in the ordinary type of machine, will show the same effect of sudden stiffening, particularly at slow rates of loading. A uniform application of load should be used if the greatest accuracy is to be obtained.

SUMMARY.

The results of this study of the Brinell test seem to be:

1. The hardness of annealed brass in the finished sheet sometimes varies by two or three Brinell hardness numbers in as many inches. This is shown not to be an error in the machine. It is therefore desirable to make several indentations in each sample. In view of this large variation in the material, it is unnecessary to use too much refinement on measurements.
2. Individual Brinell machines may have considerable systematic error, and some standard method of calibration should be devised.
3. One machine tested showed much greater variation than the others. Some test for this type of error should be devised.
4. A simple and inexpensive type of Brinell machine for small load is illustrated, and proved to be satisfactory.
5. A method of testing two samples at once is described.

[For Discussion of this paper see page 466.—ED.]

A NEW METHOD OF OBTAINING BRINELL HARDNESS.

By J. G. Ayers, Jr.

SUMMARY.

The object of this paper is to describe briefly some of the results obtained in an endeavor to design a type of Brinell hardness tester of simple rugged construction, rapidity of action and satisfactory accuracy for commercial testing.

Instead of using a dead load hydraulically applied as in the general type of Brinell machine, a definite impact was employed. This impact was obtained by fastening the Brinell ball to the bottom of a given weight and allowing it to drop from a given height onto the test specimen.

From the diameter of the impression thus produced, the true Brinell hardness number of the specimen may be obtained from a conversion table.

While as yet only the principle has been tested, it is believed a machine designed to embody this principle would have a very useful field due to the fact that it would be relatively simple in construction, rapid in action and sufficiently accurate for most commercial testing.

A NEW METHOD OF OBTAINING BRINELL HARDNESS.

BY J. G. AYERS, JR.

The present types of Brinell machines generally follow the original Brinell principle of forcing a ball of standard diameter into the steel under test by means of a standard load hydraulically applied. Several seconds are required to bring the full load to bear upon the ball and test specimen, and several more are used in maintaining this pressure, according to approved practice.

Under laboratory conditions, where time is not so important a factor as accuracy, the present types of machines are entirely satisfactory. There are cases, however, where testing must be done on a large commercial scale, as in the acceptance of raw material, and where the hardness range permissible does not require tests of laboratory accuracy. In such cases the rapid and approximate determination of the hardness of thousands of pieces is more important and productive of better results than the extremely accurate testing of a limited number whose hardness, unfortunately, is not always representative of the lot as a whole.

With the idea of overcoming this objection and of making possibly a simpler machine which, while not possessing the accuracy of the ordinary Brinell machine, would be capable of giving results that would be satisfactory for tests on a commercial scale, the writer has conducted experiments which have led to results far more encouraging than he had hoped. While the final form of the machine, including the necessary mechanical details, has not yet been developed, a description of the principle involved and the results obtained in the various experimental tests may prove of interest.

Instead of applying a standard dead load as in the ordinary Brinell machine, a given or standard impact was used. It is of course impossible to choose a standard impact that will produce the equivalent Brinell impression in a steel of any hardness, but for a given Brinell hardness it is possible to determine empirically the impact required to produce an impression identical with the one produced by the standard Brinell machine. It was decided to choose that impact which gives a 3-mm. diameter impression in a steel of 418 Brinell hardness. This impact would therefore give the same result on a steel of this hardness as the standard Brinell machine using a 10-mm. ball and a 3000-kg. load. A cylindrical 10-kg. weight with a cone-shaped lower end was used, in which the standard 10-mm. ball was fastened securely. See Fig. 1. The proper height from which the weight should fall to produce a 3-mm. diameter impression was determined experimentally by raising it to various heights by means of a supporting wire and hand crank and then severing the wire. This height was found to be 70 mm., and the impact would therefore be 0.700 m-kg. Using this impact as a standard, specimens of various Brinell hardness were tested by this device and the diameters of the impressions obtained were plotted as ordinates against the standard Brinell machine hardness numbers as abcissas. Fig. 2 shows the results obtained.

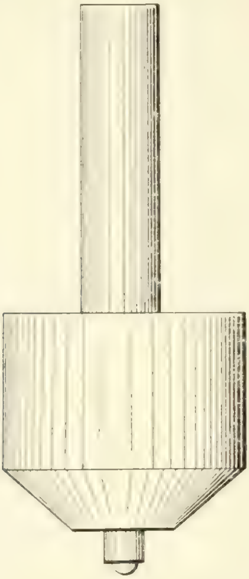


FIG. 1.

As it is sometimes advisable to use a lighter load than

3000 kg. with the standard Brinell machine, it was decided also to try the effect of a lesser impact. Instead of taking one-half the standard impact of 0.700 m-kg., that height of fall was determined which would give a 3-mm. diameter impression in a steel of 209 Brinell hardness using the same 10-kg. weight and 10-mm. ball. In other words, the new device would give the same result on a steel of this hardness as the standard Brinell machine using a 10-mm. ball and 1500-kg. load. This height was found to be 36 mm., giving an impact of 0.360 m-kg. The results of tests made on steels of different Brinell hardness are shown in Fig. 3.

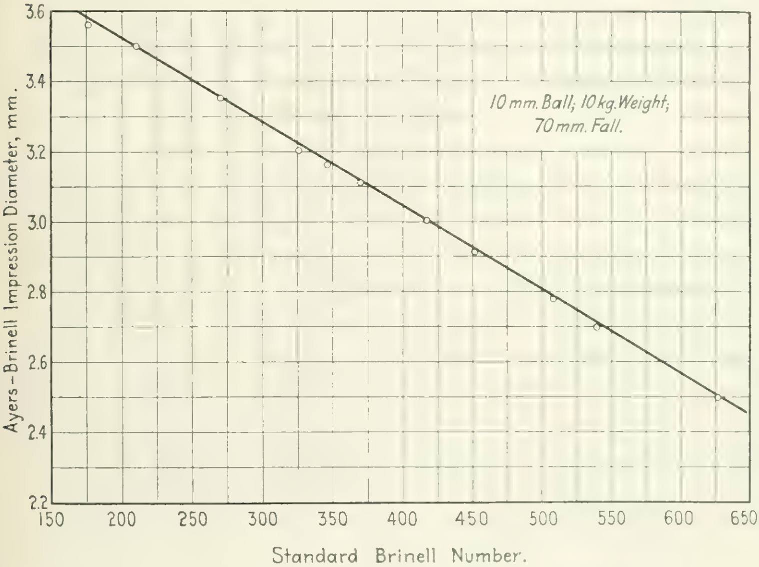


FIG. 2.—Hardness-Impression Curve for 70-mm. Fall.

In Figs. 2 and 3 the hardness-impression curve is practically a straight line and the points experimentally determined fall as closely to this line as could be desired, considering that in no case does their deviation from the line amount to a greater distance than that corresponding to the error involved in the microscopical determination of the diameter of the impression. Repeated tests gave excellent checks in all cases and showed that this method is consistently accurate and free from erratic tendencies. Each determination can be read directly in standard Brinell numbers by the use of Table I, the data for which has been obtained from Figs. 2 and 3.

By hypothesis the hardness-impression curve of the standard Brinell machine would pass through that of the "Ayers-Brinell" machine at a hardness of 418 and 209 (standard Brinell) in Figs. 2 and 3, respectively. This serves as a convenient means of checking the latter machine with the standard machine by using test specimens of this hardness.

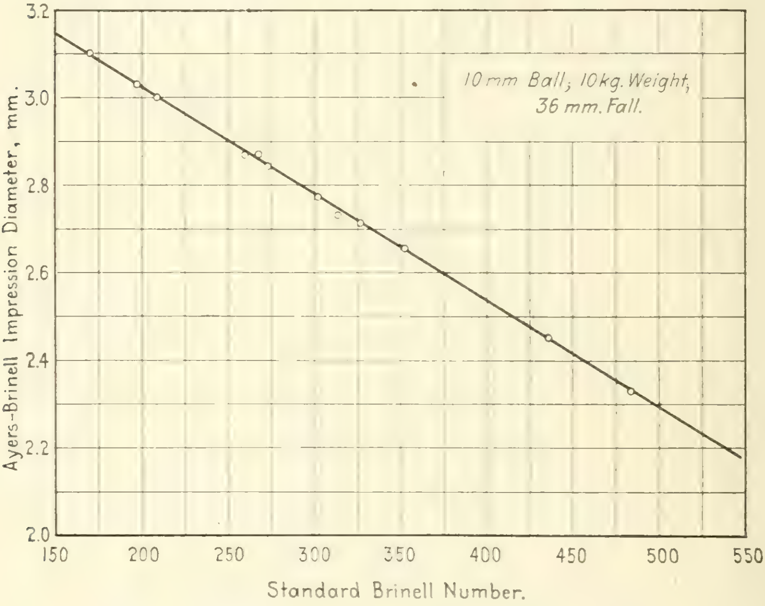


FIG. 3.—Hardness-Impression Curve for 36-mm. Fall.

As in the case of the standard Brinell machine, there are certain limitations to all ball hardness testers. In those cases in which the metal is extremely hard a permanent deformation of the ball results. Where the test specimen is soft, the ball penetrates so closely to the supporting surface or anvil that the hardness of the latter affects the results. Small narrow specimens of hard steel crack under test and soft narrow ones permit of an easy lateral flow which affects the accuracy of the test.

Fortunately, with the exception of thin pieces such as sheets, none of the above cases are so extremely common as to materially curtail the use of the Brinell machine. In the case of thin soft sheets, by reducing the load to 1000 kg. or by reducing the size of the ball consistent results can be obtained; with the device described it is necessary to use a smaller ball and less impact.

In the standard Brinell machine there are only two factors which can be varied, namely, the load and the size of ball. In the device described the weight, the height, and the diameter of the ball may be varied. Just what values will eventually be assigned to these factors has not as yet been determined.

TABLE I.—BRINELL HARDNESS NUMBERS FOR "AYERS-BRINELL" MACHINE.

10-MM. BALL ; 10-KG. WEIGHT.

Diameter of Ball Impression, mm.	Hardness Numbers.		Diameter of Ball Impression, mm.	Hardness Numbers.		Diameter of Ball Impression, mm.	Hardness Numbers.		Diameter of Ball Impression, mm.	Hardness Numbers.	
	36-mm. Fall.	70-mm. Fall.		36-mm. Fall.	70-mm. Fall.		36-mm. Fall.	70-mm. Fall.		36-mm. Fall.	70-mm. Fall.
2.00	629	838	2.50	419	628	3.00	209	418	3.50	...	208
2.05	608	817	2.55	398	607	3.05	188	397	3.50	...	187
2.10	587	796	2.60	377	586	3.10	167	376	3.60	...	166
2.15	566	775	2.65	356	565	3.15	146	355	3.65	...	145
2.20	545	754	2.70	335	544	3.20	125	334	3.70	...	124
2.25	524	733	2.75	314	523	3.25	104	313	3.75	...	103
2.30	503	712	2.80	293	502	3.30	83	292	3.80	...	82
2.35	482	691	2.85	272	481	3.35	62	271	3.85	...	61
2.40	461	670	2.90	251	460	3.40	41	250	3.90	...	40
2.45	440	649	2.95	230	439	3.45	20	229	3.95	...	19

In designing a machine upon the principle described it is possible to have it either hand or power operated. The weight can be raised and tripped at as rapid a rate as the samples can be supplied and removed, so that it will work if required with the regularity of a shear or punch press. The cost of manufacture will be less than that of the standard Brinell machine, since there are fewer accurately machined parts required, and this together with the rapidity with which tests can be made should, in the writer's opinion, create a useful field for a device of this nature.

DISCUSSION.

Mr. Cowdrey. MR. I. H. COWDREY.—Referring perhaps to both these papers together, there are one or two questions which I should like to ask Mr. de Forest to answer, and perhaps one criticism which I should like to make with regard to the paper by Mr. Ayers. First, in the case of Mr. de Forest's paper, did he do any work that would carry out the idea of investigations, presented to this Society in 1917 concerning the effect of thickness of the specimen on hardness? And, second, can he suggest to the Society a desirable method of testing the accuracy of the hydraulic Brinell machine in which he speaks of there being a constant systematic error?

In the case of Mr. Ayers' paper, the term "New" in the title would seem a misnomer. The method outlined by Mr. Ayers really embodies the underlying principle of a machine which I saw at least three years ago, at the Massachusetts Institute of Technology during the dedication of the new buildings in 1916. This machine was devised by a former student of that institution, the principle of operation being, as nearly as I can remember, identical with that of the machine Mr. Ayers describes, except possibly it might have had the advantage of being a little more applicable commercially. It consisted essentially of a known weight, capable of freely sliding down a vertical rod, the lower end of which carried a Brinell ball. As nearly as I can see, the principle involved is the same as that described in Mr. Ayers' paper.

Mr. de Forest. MR. A. V. DE FOREST.—In reply to Mr. Cowdrey, I would say that the paper last year by Mr. Davis on Brinell hardness of rolled brass brought out the fact that the minimum thickness of specimen which can be used without introducing a new variable is at least ten times the depth of the impression. This allows the use of specimens down to 0.1 in. in thickness for annealed cartridge brass.

As to calibration there are two types of error in the hydraulic Brinell machine: a constant error due to imperfect loading

Mr. de Forrest. arrangement, and a variable error due to friction or binding. I think both might be gotten at by removing the platform table, placing the whole instrument over the cross-head of an ordinary testing machine, and accurately weighing the load. Repeated weighing should bring out any variation due to friction. A rough and ready comparison could be made on any kind of fairly uniform material by taking a sufficient number of impressions sufficiently close together.

In discussion of Mr. Ayers' paper, it may be observed that the result of any dynamic method depends on how much work is lost from the specimen at the time of the blow; therefore mass, method of holding, and position of depression in relation to the center of gravity, each has an effect. In massive specimens the error due to these effects may be negligible, but in small ones large errors may be introduced, as in the scleroscope.

Mr. Sadtler. MR. C. B. SADTLER.—I think the machine referred to by Mr. Cowdrey is the Keen Impact Ball Tester. I had occasion to try one of these machines for sorting a lot of mixed steel in the form of bars $\frac{5}{8}$ by 1 in. The machine was simple in action and permitted of speedy testing, but gave unreliable results in the case of the two grades of steel tabulated below. The Brinell test, however, showed up very wide and easily observed differences. In fact, the surface of the hot-rolled bars required no dressing whatever to make a good enough Brinell test to sort the steel.

Grade No.	Chemical Composition, per cent.					Keen Impact. Diameter, mm.	Brinell Test.	
	C.	Mn.	P.	S.	Si.		Diameter, mm.	Number.
1.............	0.16	0.66	0.007	0.135	0.03	4.40 – 4.80	5.70 – 5.85	107 – 101
2.............	0.45	1.62	0.022	0.041	0.04	4.20 – 4.40	4.20 – 4.30	207 – 196

Following are certain data relating to the Keen Impact Tester:

Diameter of steel ball..................	0.554 in. (14.05 mm.)
Stationary part.........................	3.56 lb. (1.613 kg.)
Falling weight..........................	3.11 lb. (1.410 kg.)
Height of fall..........................	28.69 in. (728.5 mm.)

Mr. Sadtler. The above test data were obtained from laboratory tests on carefully prepared specimens. In doing the testing on a production basis, however, the Keen impact values covered a much wider range than given above for both grades of steel, and consequently were worthless as a basis for sorting the steel.

Mr. Holz. MR. HERMAN A. HOLZ.—Evidently Mr. Ayers has not been aware of the fact that a great deal of work has been done in the past on dynamic ball tests and that quite a number of apparatus have been designed to carry this work out. Brinell himself studied this particular problem about seventeen years ago, and the results of his systematic research were submitted, in 1906, to the Congress of the International Association for Testing Materials, in a paper by Brinell and Dillner, entitled "The Brinell Hardness Test and Its Practical Application." In this paper we find a special section on impact ball tests, giving results of comparative tests using dynamic and static ball penetration, and also a description of a device designed by Brinell to carry out such impact ball tests. Brinell started his investigation in a manner similar to that employed by Mr. Ayers. He made a static Brinell test on a piece of annealed 0.10-per-cent carbon steel, at 3000 kg. pressure, and then found by repeated trials the height through which a 5-kg. weight

TABLE I.

Carbon, per cent.	Hardness Number for Static Test at 3000 kg. Load.	Hardness Number for Impact Test at 2.25 Kilogram-Meters of Energy.
0.10	116	116
0.20	134	121
0.30	159	131
0.40	163	137
0.50	179	143
0.60	212	153
0.70	217	166
0.80	241	179
0.90	311	202
1.00	311	212

Mr. Holz.

had to fall to produce an impression of equal diameter. He found that on a 0.10-per-cent carbon steel an energy of impact of 2.25 kg.-m. produced an impression of the same diameter as a gradually applied load of 3000 kg. The main difference between the investigations of Brinell and Mr. Ayers seems to lie in the fact that Brinell varied the carbon percentage of his steel specimens, while it appears that Mr. Ayers varied only the dynamic energy employed and thus arrived at his conclusions by working on one and the same kind of steel throughout the tests. Some of Brinell's results are given in the accompanying Table I.

Brinell shows that the harder the metal is, the greater is the difference between the hardness numbers determined by using a gradually applied static load and those determined by impact. From the above it will be seen that Mr. Ayers' curves (Figs. 2 and 3) are somewhat misleading, as they can hold true only for steel of one certain chemical composition. This is further substantiated by results obtained by Brinell and Roos shown in Table II.

TABLE II.

Height of Fall of 5 kg. Weight, mm.	1.20-per-cent Carbon Steel.		0.10-per-cent Carbon Steel.	
	Diameter of Impression, mm.	$\frac{A^2}{Q}$	Diameter of Impression, mm.	$\frac{A^2}{Q}$
50	2.625	1.21	3.20	2.73
100	3.10	1.20	3.80	2.76
150	3.45	1.24	4.20	2.81
200	3.65	1.18	4.525	2.89
300	4.05	1.21	5.00	2.95
400	4.375	1.25	5.35	2.97
500	4.575	1.21	5.65	3.01

A = area of impression.
Q = energy of impact.

These results show that for the same material and the same diameter of ball, the relation between the area of impression and the applied energy of impact is fairly constant. Mr. Ayers' Table I, for use with the "Ayers-Brinell" machine, will, therefore, give fairly accurate results on tests of steel of the

Mr. Holz. same composition as that used in Mr. Ayers' investigation, but will be of no value on any other metal. In other words, metals and alloys will behave differently under dynamic forces than under static load. Mr. J. O. Roos of Stockholm attempted to find a correction formula to convert results of impact into standard static ball hardness units. His researches are published in Brinell and Dillner's paper mentioned above. He finds that $\frac{H_s^2}{H}$ = a constant, where H_s is hardness under impact and H is hardness under static load. His experimental data, however, show that this constant differs with the nature of the material, although it is independent of the temperature of annealing on the same steel. I do not believe that such a correction formula to cover metals of different nature can ever be established, as metals behave so differently even under identical conditions of the standard static Brinell test. The variations in the flow of metals and alloys under static pressure, resulting in positive or negative ridge formations around the ball and in differences of the state of equilibrium when the load is released, are quite considerable, and dealing with them is a difficult problem in itself, without complicating the situation by attempting to correlate the resistance to ball penetration under static load to that under dynamic force.

A rather lengthy paper on ball impact tests was published in 1910 by J. J. Schneider, who designed an instrument to carry out such tests which was similar to the Shore scleroscope, but which utilized a small steel ball instead of the hammer of the Shore instrument. A similar apparatus has been designed by Felix Robin of Paris and has become quite popular in France. These instruments, measuring the resistance of the metal to impact ball penetration, carry an arbitrary scale similar to the scale of the Shore instrument, and the height of rebound is taken as an indication of the hardness. On materials of identical chemical composition, the height of rebound should then be directly proportional to their static Brinell hardness. Keen's hardness tester is also based on the resistance of metals to ball penetration under impact and suffers from disadvantages similar to those noted above. In the Brinell meter, designed by Major Schoenfuss, most of these difficulties have been

Mr. Holz. overcome, as the ball is forced by dynamic pressure simultaneously into the metal under test and into a bar standardized under static pressure and of approximately the same hardness as the material under test. The hardness of the material tested is then equal to the ratio of the spherical areas of the two indentations multiplied by the Brinell number of the standardized bar used. An investigation of this portable Brinell meter is being made at present at the Bureau of Standards, as the apparatus has become very popular in the metal industry and has proven to be valuable in important ordnance work.

In summing up, I beg to say that Mr. Ayers' work has certainly been undertaken in the right direction. We need tests to determine how metals behave under dynamic forces, even if the results cannot be correlated to static tests. At present we test many steel products under static conditions of loading and use them under dynamic conditions. Many troubles in dies, pneumatic tools, etc., are undoubtedly due to the lack of efficient dynamic testing methods. The Charpy, Frémont, and Izod impact tests are very valuable, in coordination with other tests, but require the preparation of special test bars and are destructive tests. What is needed is a convenient method of testing metals under dynamic forces; the test results, however, should not be expressed in units which are based on static pressure and which have been universally adopted to express resistance to static forces, but should be expressed in units based on resistance to dynamic forces. If such a new unit is created, it should stand on its merits as one factor in the complete mechanical analysis of a metal section.

Mr. Lasier. Mr. E. L. Lasier (*by letter*).—The method of obtaining Brinell hardness described by Mr. Ayers, although not "new," as thus termed by the author, is one that should be developed, since the use of a portable machine based on the described method will be found of particular value in connection with the study of the hardness properties of large metal bodies—too large of course to be placed in the usual Brinell testing machine.

For illustration, the writer has in mind certain large steel castings used in the navy, such as roller-track castings, in which "abrasion hardness" and resistance to penetration—that is,

Mr. Lasier. "compression hardness"—are important properties. In roller-track castings the turret-roller paths are subject to considerable wear and indentation through the rollers; it is impossible, of course, to conceive of obtaining the Brinell hardness of turret-track castings through the use of the usual Brinell machine, and results of tests upon sample test specimens representative of such castings will in no way indicate the hardness of the metal of the real path.

In devising a means for determining the hardness of large and heavy pieces, recourse must be had therefore to some portable testing apparatus or machine. It is known, for instance, that the scleroscope is a convenient instrument for obtaining relative hardness data on approximately the same kinds of material, especially when such material is one of the harder metals. The use of the instrument, however, involves so many properties other than "hardness," that the writer does not believe that it is at this time a practical instrument for the problem at issue, because of inconsistencies and variations in readings obtained. As an illustration of the effect of properties other than hardness on the readings obtained, the fact may be mentioned that it has been found that the scleroscope reading on an alloy of 90 per cent copper and 10 per cent tin has been found to be higher than that obtained on tool steel, although there is no question as to which of the two materials possesses the greater "hardness." Inconsistencies and variations in readings obtained may be explained in part by the foregoing comment, by a lack of standardization in the preparation of the surfaces upon which the test is made, and in general by the different practices of individual laboratorians in making the test. The development of some other portable tester which will yield more consistent test results is therefore desirable.

It is especially pertinent that Mr. Ayers has laid emphasis in his paper on the need of making compression hardness tests (other than by the usual Brinell testing machine) with a full knowledge of the pressure or force used. It would appear that until a machine is devised which, while possibly of the same general nature as the Brinell meter, promises the obtainment of impressions in the material under test and the standard test bar, if such be used, under a known or standardized pressure,

Mr. Lasier. variations in readings on the same material will occur, such errors being greater than the usual variations in readings due to inhomogeneity in metal, mechanical errors in machine and experimental errors in observation; if such is not the case, as shown by results of conclusive tests, the writer suggests that such test results be reported by the investigators making the tests. The reason for this presumption is that in obtaining ball impressions without knowledge of the load or pressure used to obtain them, it is assumed that the Brinell hardness numeral is inversely proportional to the square of indentation and is independent of the pressure. This is undoubtedly not the fact. It is known that for certain materials there is a straight line relation between the depth of the indentation and the pressure, but that a parabolical relation exists between the diameter of indentation and the pressure; this has been shown by R. P. Devries.[1] For purposes of convenience two curves shown by Mr. Devries in illustrating results of tests obtained on a specially prepared bar of Bessemer steel are given herewith as Fig. 1. This bar was subjected to a temperature of 860° C. for one hour in an electrically heated furnace. It was then cooled to room temperature in eight hours. The depth and diameter of indentations made by loads ranging between 200 and 3000 kg. were accurately measured. In connection with the tests reported upon and graphically shown in Fig. 1, the following comment by Mr. Devries is of interest:

> "It is sometimes difficult to measure the diameter of an indentation accurately because the line of demarcation between indented and unindented metal is not always well defined. In the case of softer metals it is far from being circular. The special steel bar and most of the harder metals showed a well-defined bounding edge and the diameter of indentation was therefore easily measured."

It will be noted from Fig. 1 that the relation between load and diameter of indentation is not a straight line relation,

---

[1] "Comparison of Five Methods used to Measure Hardness," *Technologic Paper No. 11*, U. S. Bureau of Standards (1912).

Mr. Lasier. but is expressed by a parabolic curve whose equation is approximately

$$d^2 = 0.000108\ L$$

in which d is the diameter of indentation in millimeters and L is the load in kilograms. While a plot of the relation between the load and the *square* of the diameter of indentation would be a curve more nearly linear than the curve given in Fig. 1 of the relation between the load and the diameter of indentation, it would still be far from a straight line.

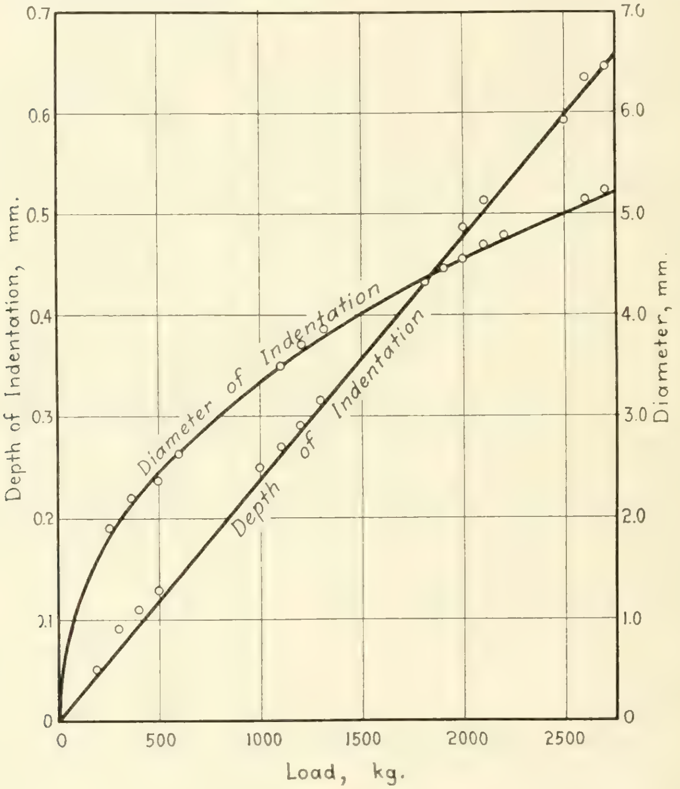


FIG. 1.—Indentation-Load Curves for Bessemer Steel Bar.

It is therefore evident that when no definite load or pressure is used, but on the contrary any convenient (and unknown)

Mr. Lasier.

pressure, such as that obtained from the blow of a hammer, etc., there is a source of error in the use of an instrument or machine embodying that principle for the reason given if for no other; hence it becomes necessary to modify and standardize such a test so as to specify a definite (*a*) conditioning of surface and (*b*) pressure used to obtain the indentation. It will probably also be necessary to use as a "standard reference bar" metal having approximately the same Brinell hardness numeral at the pressure used as has the material under test. It would also be necessary when standard bars are used for reference, to have some assurance that such standards are of fairly uniform hardness and have been suitably calibrated, for the comments of Mr. de Forest in his paper to the effect that "the hardness of annealed brass in the finished sheet sometimes varies by two or three Brinell hardness numbers in as many inches" are unfortunately too true. In this connection it may be of interest to recall the conclusions reached several years ago by Harold Moore[1] of the Woolwich Arsenal, England, in his tests for uniformity on mild steel, brass, copper and nickel-chromium steel specially heat treated to give uniform hardness. All of Mr. Moore's tests were made in a 4000-kg. multiple lever machine, the load being slowly applied and maintained for ten seconds at the maximum load. Impressions were measured by a microscope to 0.001 mm., the diameter of impression finally adopted being in each case the mean of two diameters at right angles to each other. The test plates were planed smooth on both faces and the face in which the impressions were obtained was polished. In the tests for uniformity three to seven impressions in each of two or more plates of each material were obtained, using the same ball and load. The greatest difference found by Mr. Moore was 2 per cent of the diameter of impression in the case of mild steel, and not over 1 per cent in the case of the brass and hard steel.

Mr. Holz.

MR. HOLZ (*by letter*).—Mr. Lasier's troubles in testing roller-track castings are caused primarily by the fact that resistance to wear and resistance to ball penetration are properties of different nature. Several years ago, a special machine was constructed

---

[1] "Investigations on the Brinell Method of Determining Hardness," *Proceedings*, Inter. Assoc. Test. Mats., Fifth Congress, Copenhagen, 1909.

Mr. Holz. in Belgium, at the Derihon Works, to determine directly this resistance to wear, and by the use of this excellent machine, it was proven conclusively that the wearing properties of iron and steel, which are largely influenced by manganese content, are not functions of Brinell hardness. This question has also been recently investigated in England, and the very interesting "Report of the Hardness Tests Research Committee,"[1] contains valuable information on this point.

Undoubtedly a large demand exists for portable hardness testing devices which permit of tests on forgings, castings, etc., without regard to their dimensions. In the portable "Brinell Meter," the ratio between the spherical areas of two indentations produced simultaneously in a standard material of known Brinell hardness and the material under investigation permits us to determine the Brinell hardness of the unknown material. The accuracy of the determination depends only upon judicious use of the meter, as is the case in the use of any testing instrument. Just as a metallurgist would not expect the Shore scleroscope to give comparative results on copper-tin alloys, steels, and rubber, so would no testing engineer using the "Brinell Meter" choose a standard of hardened brass for testing of annealed steel, or vice versa. Many metallurgists in using this apparatus prepare their own standards from the material which they have to investigate. This makes the instrument a very practical one and eliminates the sampling error, permitting Brinell tests at any choosen spot on a large forging, gun barrel, armor plate, etc.

Mr. Lasier refers to Mr. Devries' work on the technique of determining accurately the area of Brinell impressions. For research work, the depth measurement by optical means is undoubtedly the best practice, but in industrial laboratory tests the diameter measurement is preferable and is required in the standard specifications of the Ordnance Dept., Aircraft Production Dept., the S. A. E., and A.S.T.M. There are means available for measuring a diameter of two to six millimeters with an accuracy of $\frac{1}{10}$ mm. with far greater precission than there are for measuring a corresponding depth of from 10 to 1 mm. with an accuracy of $\frac{1}{100}$ mm. to 1 mm. Several types of direct-reading depth gages for use with Brinell testing machines have recently been developed. They work on the spring and lever principle and cannot possibly be reliable and accurate to within $\frac{1}{100}$ mm. What we see with our own eye, in a measuring microscope, is as correct as human power can make it, and for this reason the diameter measurement by means of micrometer microscope will undoubtedly remain the standard practice in industrial work. **Mr. Holz.**

---

[1] Institution of Mechanical Engineers, (London).

The sum of the other errors caused in Brinell tests (rate in kilograms per second in increasing the load, deformation of the steel ball, inaccuracy of pressure gages, etc.) are far greater than the differences caused by diameter measurement, but it would lead too far to go into details at this occasion. The metallurgist knows, of course, the limitations of every testing method, and the main limitation of the Brinell and other hardness tests is that metal sections showing identical Brinell or other hardness units may have entirely different mechanical properties. Some may be brittle and others may possess great strength such differences in iron and steel are clearly and unmistakably revealed by the method of "magnetic analysis."

SUMNER ELASTIC-LIMIT RECORDER.

By J. L. Jones and C. H. Marshall.

SUMMARY.

The necessity for a more convenient method of determining the elastic limit has long been felt. The semi-automatic solenoid device described in this paper is accurate and rapid, and enables one man to do the work that has usually required three men. It has been in use in connection with the Ewing extensometer over a considerable period of time and the data obtained have been uniformly satisfactory.

One especially valuable feature is the fact that the card on which the test is made can be filed as a permanent record.

SUMNER ELASTIC-LIMIT RECORDER.

BY J. L. JONES AND C. H. MARSHALL.

The method that is usually followed in testing laboratories in making elastic-limit determinations is to have one person read the elongation with an extensometer, another operate the testing machine and read the load applied, while a third person acts as a clerk and records the readings. This method is too slow for commercial work and it multiplies the liability of error due to personal equation.

There has been in use in the physical testing laboratory of the Westinghouse Electric and Manufacturing Company at East Pittsburgh, Pa., since 1909, an instrument that very much facilitates the taking of accurate elastic limits. The original design was made by Mr. J. N. Sumner, an engineering apprentice, since deceased. It has been modified at various times and its present form is shown diagrammatically in Fig. 1. The method of attachment to the testing machine is shown in Fig. 2, which represents the instrument in actual use. In Fig. 3 the instrument is shown to an enlarged scale, with the card in position for recording.

This recorder may easily be applied to the standard testing machine and by its use a single person can accurately determine the elastic limit of any sample that is being tested in tension or compression.

The apparatus consists of a semi-automatic load-indicating mechanism which is attached to the testing machine by means of a frame, as shown in Fig. 2. The recorder can be moved to the right or left and fastened securely in any desired position by means of a set screw. The vertical rows of holes in the standards at each end (only the standard at the left end of the frame appears in the illustration) allow the recorder to be raised or lowered at will.

Attached to the weighing poise is a card graduated to conform to the graduations of the beam, the range being from zero to 12,000 lb., with a minimum reading of 100 lb. This allows a standard 4 by 6-in. filing card to be used and the results are sufficiently accurate for commercial work. As the limit of accuracy of weighing on a testing machine of 100,000-lb. capacity is about 50 lb., it might be desirable to have the minimum reading of the card 50 instead of 100 lb. This can be easily accomplished by increasing the length of the card to 12 in. and reducing the weight of the poise one-half, thus doubling its rate of travel.

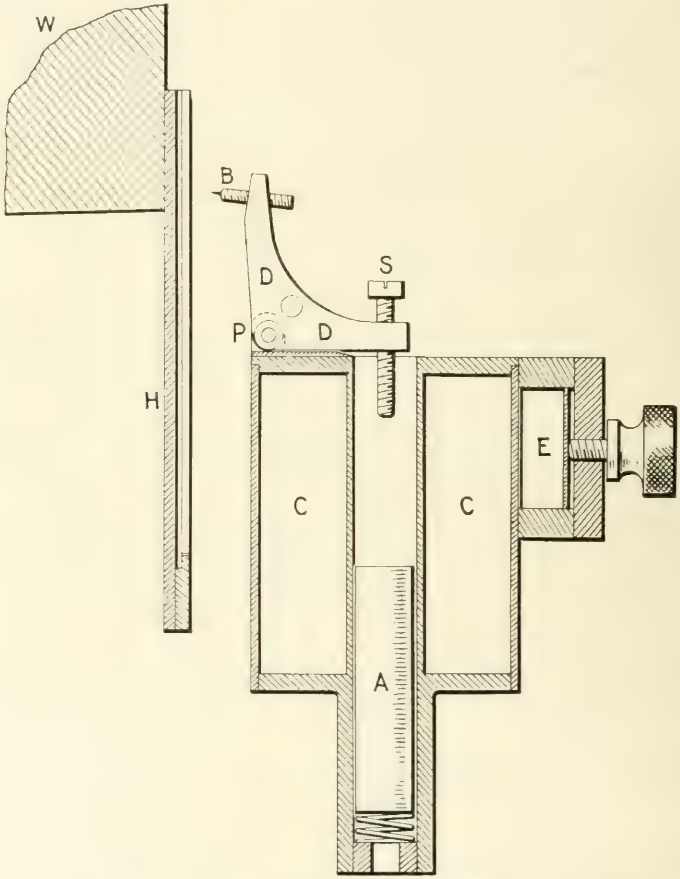


FIG. 1.—Diagrammatic Illustration of Sumner Elastic-Limit Recorder.

On the back of the card spaces are ruled in which may be recorded the serial number of the sample tested, ultimate (beam) load, elongation in 2 in., and the reduced diameter. After the elastic limit is determined the card is filed so as to be available in case a complete curve is subsequently desired.

DESCRIPTION OF THE RECORDER.

The recorder is shown in detail in Fig. 1. It is essentially a solenoid with a loosely fitting armature, *A*. When at rest the armature is at the bottom of the tube as shown, but when current is flowing through the coil, the center of the armature will be at the center of the coil. The adjustable screw, *S*, is set so that it will just touch the armature when it is in this position.

If the armature is at rest at the bottom of the tube and the circuit is closed it will be pulled up and its inertia will carry it past the center of the coil so that it will hit the screw *S* a hammer blow. It will then drop to the center of the coil where it will be held until the circuit is broken, when it will drop to the bottom of the tube.

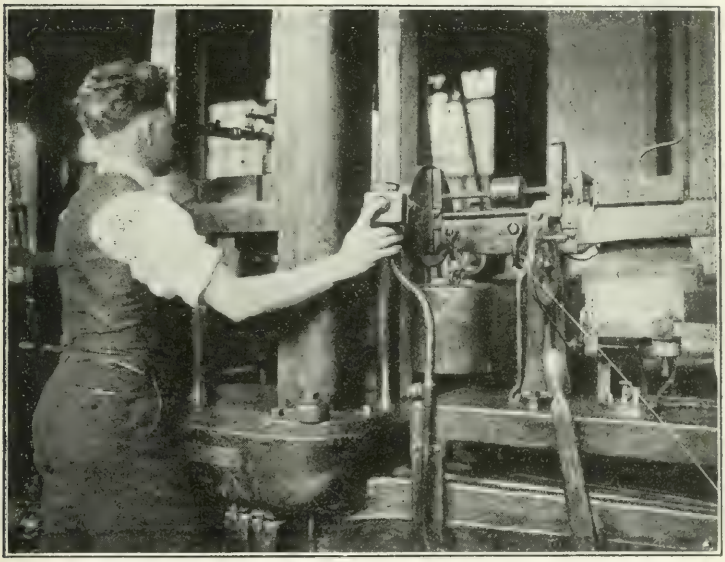


FIG. 2.—Attachment of Recorder to Testing Machine.

The bell crank, *D*, is pivoted at *P* so that when the armature hits *S*, the motion is transmitted to the prick punch *B*, which is driven sharply against the card in the holder *H*, making a small pin hole in the card and immediately returning to its normal position, allowing the card to continue its movement. A light spring (not shown) on the crank assists it in returning to its normal position.

In the bottom of the tube is a short spring which acts as a shock absorber for the armature. A clamp, *E*, on the side of the recorder serves for mounting it on the frame.

The frame consists of two upright pieces fastened to the machine, with a cross-piece on which the recorder is mounted by means of the clamp *E*. The recorder can be slid along this cross-piece in order to set it so that it starts at the zero point; and also in order to reset it, which is necessary when the load at the elastic-limit exceeds 12,000 lb., as the record must then be run across the card a second time.

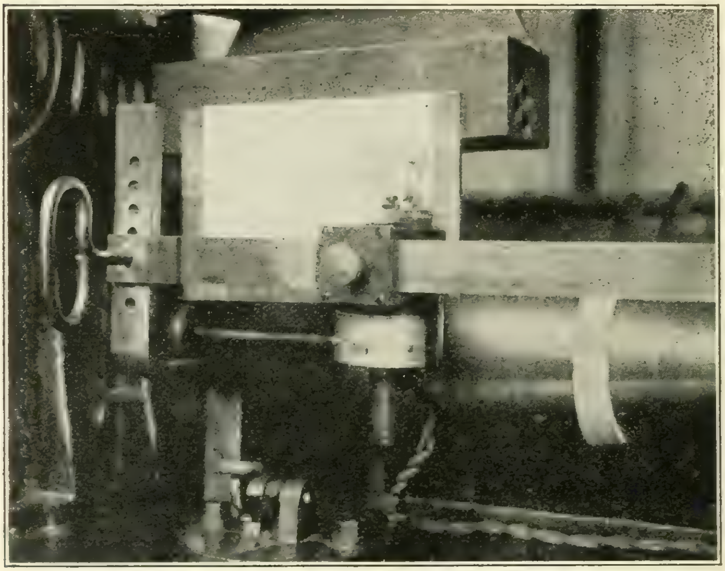


FIG. 3.—Enlarged View of Recorder.

The uprights have holes drilled about $\frac{1}{2}$ in. apart so that the height can be adjusted and the position of the recorder changed. In this way several tests can be put on one card.

A push button for operating the recorder is located where the operator can conveniently reach it while he is watching the extensometer.

The card holder is made of aluminum and is fastened securely to the poise. A hole is drilled in the poise to remove a weight equal to that of the holder.

METHOD OF OPERATION.

When using the recorder, the test specimen is placed in the machine in the usual way, with the extensometer in position. The card is then placed in the holder and fastened so that it cannot shift. The poise is then set so that the beam reads zero load and the recorder is slid along the cross bar until when the button is pressed the punch mark is on the zero line on the card. The recorder is clamped in this position, the machine started, and the operator stations himself at the extensometer. When the extensometer shows predetermined elongations, such as 0.0002, 0.0006 in., etc., he presses the button. As the card attached to the poise is moving in front of the recorder, which is stationary, and as the card is graduated to correspond to the beam, the punch marks will indicate the load at which the elongation is measured.

The operation is continued until the elastic limit is reached, after which the extensometer is removed and the yield point determined. The test is completed in the usual manner, the record being made on the back of the card.

For the next test, the recorder can be moved down to the next position and in this way five or six tests may be grouped on the same card. After the tests are completed the card is removed and curves plotted. The elastic limit or proportional limit is determined from the curves, the points of which will be found to be very regular.

With this apparatus, elastic-limit determinations can be accurately and rapidly made and if the card is filed a complete record of the test is available at any time.

VOLUME XVIII, PART II.

SUBJECT INDEX.

A

Abrasion Test.
An — for Stone, Gravel and Similar Aggregates. **H. H. Scofield, 416** Discussion, 426.

Aggregates (see also **Stone, Gravel**).
An Abrasion Test for Stone, Gravel and Similar —. **H. H. Scofield, 416** Discussion, 426.
Proportioning the Materials of Mortars and Concretes by Surface Areas of —. L. N. Edwards, 235. Discussion, 284.

Airplane.
Transverse Testing under Non-Uniformly Distributed Load with Special Application to — Wing Ribs. Irving H. Cowdrey, 429.

Analysis.
The Evaluation of Zinc Dust: A Proposed Method of —. L. A. Wilson, 220.

Anchor Chain.
Cast Steel —. H. Jasper Cox, 98. Discussion, 114.

Areas.
Proportioning the Materials of Mortars and Concretes by Surface — of Aggregates. L. N. Edwards, 235. Discussion, 284.

Artillery Cases.
Topical Discussion on Season and Corrosion Cracking of Brass. The Prevention of Season and Corrosion Cracking of Brass — by Special Heat Treatment. W. B. Price, 179.

B

Brass.
Topical Discussion on Season and Corrosion Cracking of —. William Campbell, W. H. Bassett, W. Reuben Webster, P. D. Merica and R. W. Woodward, W. B. Price, Henry S. Rawdon, 147. General Discussion, 201.

Brick.
The Necessity for Inspection and Testing of Refractory —. C. E. Nesbitt and M. L. Bell, 336. Discussion, 346.

Brinell.
A New Method of Obtaining — Hardness. J. G. Ayers, Jr., 460. Discussion, 466.
A Simple Type of — Testing Machine for 500 kg. load. A. V. de Forest, 449. Discussion, 466.

C

Canning Industry.
Topical Discussion on Cooperation in Industrial Research. Cooperative Research in the American —. Frank E. Gorrell, 40.
Cast Steel.
— Anchor Chain. H. Jasper Cox, 98. Discussion, 114.
Cement.
Silica —. R. J. Montgomery, 350.
Corrosion Cracking.
Topical Discussion on Season and — of Brass. William Campbell, W. H. Bassett, W. Reuben Webster, P. D. Merica and R. W. Woodward, W B. Price, H. S. Rawdon, 147. General Discussion, 201.
Chain.
Cast Steel Anchor —. H. Jasper Cox, 98. Discussion, 114.
Concrete.
Effect of Age on the Strength of Concrete. Duff A. Abrams, 317.
Topical Discussion on Cooperation in Industrial Research. Cooperation of the Portland Cement Association and Lewis Institute in Experimental Studies of —. Duff A. Abrams, 56.
Effects of Grading of Sands and Consisting of Mix upon the Strength of Plain and Reinforced —. L. N. Edwards, 303.
Proportioning the Materials of Mortars and Concretes by Surface Areas of Aggregates. L. N. Edwards, 235. Discussion, 284.
Consistency.
Effects of Grading of Sands and Consistency of Mix upon the Strength of Plain and Reinforced Concrete. L. N. Edwards, 303.

D

Deposits.
The Sampling of — of Road Stone and Gravel in the Field. L. Reinecke and K. A. Clark, 393. Discussion, 414.

E

Elastic Limit.
Summer — Recorder. J. L. Jones and C. H. Marshall, 478.
Engine.
Internal-Combustion —: Lubrication and Lubricants. P. H. Conradson, 387.

F

Field.

The Sampling of Deposits of Road Stone and Gravel in the —. L. Reinecke and K. A. Clark, 393. Discussion, 414.

G

Grading.

Effects of — of Sands and Consisting of Mix upon the Strength of Plain and Reinforced Concrete. L. N. Edwards, 303.

Grain Size.

— of Iron as Affected by Temperature. D. J. McAdam, Jr., 68. Discussion, 82.

Gravel (see also **Stone, Aggregates, Concrete**).

An Abrasion Test for Stone, — and Similar Aggregates. H. H. Scofield, 416. Discussion, 426.

The Sampling of Deposits of Road Stone and — in the Field. L. Reinecke and K. A. Clark, 393. Discussion, 414.

H

Hardness.

A New Method of Obtaining Brinell —. J. G. Ayers, Jr., 460. Discussion, 466.

Heat Treatment.

Topical Discussion on Season and Corrosion Cracking of Brass. The Prevention of Season and Corrosion Cracking of Brass Artillery Cases by Special —. W. B. Price, 179.

I

Industrial Research.

Topical Discussion on Cooperation in —. Developments in —. Charles L. Reese, 32.

Topical Discussion on Cooperation in —. Organization of —. Arthur D. Little, 22.

Initial Stress.

Topical Discussion on Season and Corrosion Cracking of Brass. — and Corrosion Cracking. P. D. Merica and R. W. Woodward, 165.

Inspection.

The Necessity for — and Testing of Refractory Brick. C. E. Nesbitt and M. L. Bell, 336. Discussion, 346.

Internal-Combustion Engine.

See **Engine.**

Iron.

Grain Size of — as Affected by Temperature. D. J. McAdam, Jr., 68. Discussion, 82.

L

Load.

A Simple Type of Brinell Testing Machine for 500 kg. —. A. V. de Forest, 449. Discussion, 466.

Transverse Testing under Non-Uniformly Distributed — with Special Application to Airplane Wing Ribs. Irving H. Cowdrey, 429.

Lubricants.

Internal-Combustion Engine: Lubrication and —. P. H. Conradson, 387.

Lubrication.

See **Lubricants.**

M

Machine.

A Simple Type of Brinell Testing — for 500 kg. Load. A. V. de Forest, 449. Discussion, 466.

Materials (see also **Aggregates**).

Proportioning the — of Mortars and Concretes by Surface Areas of Aggregates. L. N. Edwards, 235. Discussion, 284.

Measurement.

The Variable-Pressure Method for the — of Viscosity. E. C. Bingham, 373. Discussion, 384.

Mercury Solutions.

Topical Discussion on Season and Corrosion Cracking of Brass. The Use of — for Predicting Season Cracking in Brass. Henry S. Rawdon, 189.

Method (see also **Tests**).

A New — of Obtaining Brinell Hardness. J. G. Ayers, Jr., 460. Discussion, 466.

The Variable-Pressure — for the Measurement of Viscosity. E. C. Bingham, 373. Discussion, 384.

The Evaluation of Zinc Dust: A Proposed — of Analysis. L. A. Wilson, 220.

Mix (see also **Mortars**).

Effects of Grading of Sands and Consistency of — upon the Strength of Plain and Reinforced Concrete. L. N. Edwards, 303.

Mortars (see also **Concrete**).

Proportioning the Materials of — and Concretes by Surface Areas of Aggregates. L. N. Edwards, 235. Discussion, 284.

P

Pipes.

Topical Discussion on Season and Corrosion Cracking of Brass. Season Cracking and Splitting of Condenser Tubes and —. William Campbell, 147.

Plain Concrete (see also **Concrete**).

Effects of Grading of Sands and Consisting of Mix upon the Strength of Plain and Reinforced Concrete. L. N. Edwards, 303.

Pressure.
The Variable — Method for the Measurement of Viscosity. E. C. Bingham, 373. Discussion, 384.
Proportioning.
— the Materials of Mortars and Concretes by Surfaces Areas of Aggregates. L. N. Edwards, 235. Discussion, 284.
Proposed Method.
See **Method.**

R

Recorder.
Sumner Elastic-Limit —. J. L. Jones and C. H. Marshall, 478.
Refractory Brick.
See **Brick.**
Reinforced Concrete (see also **Concrete**).
Effects of Grading of Sands and Consisting of Mix upon the Strength of Plain and —. L. N. Edwards, 303.
Research.
Topical Discussion on Cooperation in Industrial —. Edgar Marburg, Henry M. Howe, John Johnston, Arthur D. Little, Charles L. Reese, Frank E. Gorrell, Alfred D. Flinn, Duff A. Abrams, J. S. Unger and S. R. Church, 5.
Road Stone (see also **Gravel**).
The Sampling of Deposits of — and Gravel in the Field. L. Reinecke and K. A. Clark, 393. Discussion, 414.

S

Sampling.
The — of Deposits of Road Stone and Gravel in the Field. L. Reinecke and K. A. Clark, 393. Discussion, 414.
Sands (see also **Stone, Gravel, Aggregates**).
Effects of Grading of — and Consistency of Mix upon the Strength of Plain and Reinforced Concrete. L. N. Edwards, 303.
Saybolt.
The Standard — Universal Viscosimeter. Winslow H. Herschel, 363.
Season Cracking.
Season and Corrosion Cracking of Brass. William Campbell, W. H. Bassett, W. Reuben Webster, P. D. Merica and R. W. Woodward, W. B. Price, H. S. Rawdon, 147. General Discussion, 201.
Silica.
— Cement. R. J. Montgomery, 350.
Steel.
Cast — Anchor Chain. H. Jasper Cox, 98. Discussion, 114.
Changes within the Critical Range of a Given —: From Ac_1 to Ac_{3-2}. J. G. Ayers, Jr., 87.

Stone (see also **Gravel Aggregates**).
An Abrasion Test for —, Gravel and Similar Aggregates. H. H. Scofield, 416. Discussion, 426.
The Sampling of Deposits of Road — and Gravel in the Field. L. Reinecke and K. A. Clark, 393. Discussion, 414.

Strength.
Effects of Grading of Sands and Consisting of Mix upon the — of Plain and Reinforced Concrete. L. N. Edwards, 303.
Effect of Age on the — of Concrete. Duff A. Abrams, 317.

Surface Areas.
Proportioning the Materials of Mortars and Concretes by — of Aggregates. L. N. Edwards, 235. Discussion, 284.

T

Temperature.
Grain Size of Iron as Affected by —. D. J. McAdam, Jr., 68. Discussion, 82.

Testing (see also **Tests**).
A Simple Type of Brinell — Machine for 500 kg. Load. A. V. deForest, 449. Discussion, 466.
Transverse — under Non-Uniformly Distributed Load, with Special Application to Airplane Wing Ribs. Irving H. Cowdrey, 429.
The Necessity for Inspection and — of Refractory Brick. C. E. Nesbitt and M. L. Bell, 336. Discussion, 346.

Tests (see also **Testing**).
An Abrasion Test for Stone, Gravel and Similar Aggregates. H. H. Scofield, 416. Discussion, 426.

Topical Discussion.
— on Cooperation in Industrial Research. Edgar Marburg, Henry M. Howe, John Johnston, Arthur D. Little, Charles L. Reese, Frank E. Gorrell, Alfred D. Flinn, Duff A. Abrams, J. S. Unger, S. R. Church, 5.
— on Season and Corrosion Cracking of Brass. William Campbell, W. H. Bassett, W. Reuben Webster, P. D. Merica and R. W. Woodward, W. B. Price, Henry S. Rawdon, 147. Discussion, 201.

Transverse Testing.
See **Testing.**

Tubes.
Topical Discussion on Season and Corrosion Cracking of Brass. Season Cracking and Splitting of Condenser — and Pipes. William Campbell, 147.

U

Universal Viscosimeter.
See **Viscosimeter.**

V

Variable-Pressure.
  See **Pressure.**
Viscosimeter (see also **Viscosity**).
  The Standard Saybolt Universal —. W. H. Herschel, 363.
Viscosity (see also **Viscosimeter**).
  The Variable-Pressure Method for the Measurement of —. E. C. Bingham, 373. Discussion, 384.

W

War Problems.
  Topical Discussion on Cooperation in Industrial Research. Cooperation between Governmental Bureaus and the Industries in Research on —. S. R. Church, 66.
Wing Ribs.
  Transverse Testing under Non-Uniformly Distributed Load with Special Application to Airplane —. Irving H. Cowdrey, 429.

Z

Zinc Dust.
  The Evaluation of —: A Proposed Method of Analysis. L. A. Wilson, 220.

AUTHOR INDEX.

A

Abrams, Duff A.
Topical Discussion on Cooperation in Industrial Research: Cooperation of the Portland Cement Association and Lewis Institute in Experimental Studies of Concrete, 56.
Effect of Age on the Strength of Concrete, 317.
Discussion, 292.

Ayers, J. G. Jr.
Changes within the Critical Range of a Given Steel: From Ac_1 to Ac_{3-2}, 87.
A New Method of Obtaining Brinell Hardness, 460.

B

Bassett, W. H.
Topical Discussion on Season and Corrosion Cracking of Brass: The Causes and Prevention of Corrosion Cracking, 153.
Discussion, 212, 213.

Bates, P. H.
Discussion, 294.

Becker, R. C.
Discussion, 213.

Bell, M. L.
The Necessity for Inspection and Testing of Refractory Brick, 336.

Bingham, E. C.
The Variable-Pressure Method for the Measurement of Viscosity, 373.
Discussion, 386.

Breyer, F. G.
Discussion, 212.

Brooks, C. K.
Discussion, 117, 145.

C

Campbell, William.
Topical Discussion on Season and Corrosion Cracking of Brass: Season Cracking and Splitting of Condenser Tubes and Pipes, 147.

Church, S. R.
Topical Discussion on Cooperation in Industrial Research: Cooperation between Governmental Bureaus and the Industries in Research on War Problems, 66.

Clark, K. A.
The Sampling of Deposits of Road Stone and Gravel in the Field, 393.
Conradson, P. H.
Internal-Combustion Engine: Lubrication and Lubricants, 387.
Cowdrey, Irving H.
Transverse Testing under Non-Uniformly Distributed Load with Special Application to Airplane Wing Ribs, 429.
Discussion, 466.
Cox, H. Jasper
Cast Steel Anchor Chain, 98.
Discussion, 145.

D

Davis, Watson.
Discussion, 295.

E

Edwards, L. N.
Proportioning the Materials of Mortars and Concretes by Surface Areas of Aggregates, 235.
Effects of Grading of Sands and Consistency of Mix upon the Strength of Plain and Reinforced Concrete, 303.
Discussion, 299.

F

Flinn, Alfred D.
Topical Discussion on Cooperation in Industrial Research: Development of Existing Agencies, 43.
Discussion, 201.
de Forest, A. V.
A Simple Type of Brinell Testing Machine for 500 kg. Load, 449.
Discussion, 205, 466.

G

Goldbeck, A. T.
Discussion, 288.
Gorrell, Frank E.
Topical Discussion on Cooperation in Industrial Research: Cooperative Research in the American Canning Industry, 40.

H

Herschel, Winslow H.
The Standard Saybolt Universal Viscosimeter, 363.
Discussion, 384.
Holz, H. A.
Discussion, 468, 475.

Howe, Henry M.
Topical Discussion on Cooperation in Industrial Research: General Introduction, 8.
Discussion, 218.
Howe, R. M.
Discussion, 346.

J

Jeffries, Zay.
Discussion, 82.
Johnson, Nathan C.
Discussion, 284.
Johnston, John.
Topical Discussion on Cooperation in Industrial Research: Recent Developments in Great Britain, 12.
Jones, J. L.
Sumner Elastic-Limit Recorder, 478.
Jonson, Ernst.
Discussion, 201.

L

Lasier, E. L.
Discussion, 143, 471.
Lesley, R. W.
Discussion, 288.
Little, Arthur D.
Topical Discussion on Cooperation in Industrial Research: Organization of Industrial Research, 22.

M

Marburg, Edgar.
Topical Discussion on Cooperation in Industrial Research: Opening Announcement, 5.
Marshall, C. H.
Sumner Elastic-Limit Recorder, 478.
Mathewson, C. H.
Discussion, 211.
Mattimore, H. S.
Discussion, 414, 426.
McAdam, D. J., Jr.
Grain Size of Iron as Affected by Temperature, 68.
Discussion, 85.
McKinley, J. M.
Discussion, 349.
Merica, P. D.
Topical Discussion on Season and Corrosion Cracking of Brass: Initial Stress and Corrosion Cracking, 165.

Merrill, W. L.
Discussion, 114.
Montgomery, R. J.
Silica Cement, 350.

N

Nesbitt, C. E.
The Necessity for Inspection and Testing of Refractory Brick, 336.

P

Price, W. B.
Topical Discussion on Season and Corrosion Cracking of Brass: The Prevention of Season and Corrosion Cracking of Brass Artillery Cases by Special Heat Treatment, 179.
Discussion, 209.

R

Rawdon, Henry S.
Topical Discussion on Season and Corrosion Cracking of Brass: The Use of Mercury Solutions for Predicting Season Cracking in Brass, 189.
Reese, Charles L.
Topical Discussion on Cooperation in Industrial Research: Developments in Industrial Research, 32.
Reinecke, L.
The Sampling of Deposits of Road Stone and Gravel in the Field, 393.

S

Sadtler, C. B.
Discussion, 467.
Schramm, Edward.
Discussion, 212.
Scofield, H .H.
An Abrasion Test for Stone, Gravel and Similar Aggregates, 417.
Smith, F. G.
Discussion, 210.

T

Talbot, A N.
Discussion, 291.

U

Unger, J. S.
Topical Discussion on Cooperation in Industrial Research: Some Practical Views of Research, 62.
Discussion, 348.

V

Van Doorn, H. D.
Discussion, 141.

W

Webster, W. Reuben.
Topical Discussion on Season and Corrosion Cracking of Brass: Season Cracking, 163.

Wilson, L. A.
The Evaluation of Zinc Dust: A Proposed Method of Analysis, 220.

Woodward, R. W.
Topical Discussion on Season and Corrosion Cracking of Brass: Initial Stress and Corrosion Cracking, 165.

TA
401
A5
v.18
pt.2
cop.2

~~Physical &~~
~~Applied Sci.~~
~~Serials~~
Engineering

American Society for
Testing and Materials
Proceedings

PLEASE DO NOT REMOVE
CARDS OR SLIPS FROM THIS POCKET

UNIVERSITY OF TORONTO LIBRARY

ENGIN STORAGE